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Performance evaluation within CASE_ATTI of MHT and JVC association algorithms for COMDAT TD

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14. ABSTRACT
Command Decision Aid Technology (COMDAT) is a Technology Demonstrator Project (TDP) scheduled to take place during the June 2000 to March 2007 time frame. COMDAT aims to form the basis for defining the mid-life upgrade to the Command and Control Information System (C2IS) of the HALIFAX Class frigate. The overall TD program consists of developing an integrated Maritime Tactical Picture (MTP), which is being achieved through three development cycles. Defence Research & Development Canada (DRDC) Valcartier is a partner in the COMDAT project, whose part of the contribution consists of performing an independent analysis of sea trial data to assess the performance of the MSDF technology compared the legacy Command & Control System (CCS), conducting a sensitivity analysis of COMDAT MSDF parameters and algorithms to recommend improvements for COMDAT subsequent cycles, and providing scientific advises for Multi-Sensor Data Fusion (MSDF) technology where required. This report presents the work performed under the sensitivity analysis task. The main objective of this task consists of evaluating a candidate alternative to the Jonker, Volgenant & Castanon (JVC) association algorithm, that is used by COMDAT MSDF. This candidate is the Multiple Hypothesis Tracking (MHT) association algorithm, an implemented version of which is available in DRDC Valcartier?s Concept Analysis and Simulation Environment for Automatic Target Tracking and Identification (CASE ATTI) test-bed. The report presents a comparison of the two algorithms. This comparison was motivated by a performance evaluation of COMDAT MSDF in which association performance was not as good as expected.

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Abstract

Command Decision Aid Technology (COMDAT) is a Technology Demonstrator Project (TDP) scheduled to take place during the June 2000 to March 2007 time frame. COMDAT aims to form the basis for defining the mid-life upgrade to the Command and Control Information System (C2IS) of the HALIFAX Class frigate. The overall TD program consists of developing an integrated Maritime Tactical Picture (MTP), which is being achieved through three development cycles. Defence Research & Development Canada (DRDC) Valcartier is a partner in the COMDAT project, whose part of the contribution consists of performing an independent analysis of sea trial data to assess the performance of the MSDF technology compared the legacy Command & Control System (CCS), conducting a sensitivity analysis of COMDAT MSDF parameters and algorithms to recommend improvements for COMDAT subsequent cycles, and providing scientific advises for Multi-Sensor Data Fusion (MSDF) technology where required. This report presents the work performed under the sensitivity analysis task. The main objective of this task consists of evaluating a candidate alternative to the Jonker, Volgenant & Castanon (JVC) association algorithm, that is used by COMDAT MSDF. This candidate is the Multiple Hypothesis Tracking (MHT) association algorithm, an implemented version of which is available in DRDC Valcartier's Concept Analysis and Simulation Environment for Automatic Target Tracking and Identification (CASE_ATTI) test-bed. The report presents a comparison of the two algorithms. This comparison was motivated by a performance evaluation of COMDAT MSDF in which association performance was not as good as expected.

Résumé

Command Decision Aid Technology (COMDAT) est un démonstrateur technologique qui s'étend sur la période de juin 2000 à mars 2007. L'objectif principal de COMDAT est de fournir des résultats/bases nécessaires à la modernisation du système de commandement et contrôle des frégates canadiennes de classe Halifax. L'activité majeure de ce démonstrateur technologique, réalisée en trois cycles de développement, consiste à produire une image tactique maritime unique. Recherche & développement pour la défense Canada (RDDC) – Valcartier est un partenaire clé dans le projet COMDAT. Une partie de sa contribution consiste à effectuer une analyse indépendante des données des essais en mer. Le but principal de cette analyse consiste à comparer la technologique de Fusion de Données Multi-Sources (FDMS) utilisée par COMDAT à la technologie utilisée par le système de commandement et contrôle actuel des frégates. La contribution de RDDC Valcartier à COMDAT comprend également une étude de sensibilité des paramètres/algorithmes utilisés par FDMS, afin de recommander les améliorations qui s'imposeraient. Le travail consigné dans ce document est l'analyse de sensibilité des algorithmes utilisés par COMDAT. L'objectif principal de cette activité consiste à évaluer les performances d'une solution de rechange à l'algorithme d'association Jonker, Volgenant & Castanon (JVC) utilisé dans COMDAT. Il s'agit de l'algorithme Multiple Hypothesis Tracking (MHT) dont une implantation est disponible dans le banc d'essais Concept Analysis and Simulation Environment for Automatic Target Tracking and Identification (CASE_ATTI) de RDDC Valcartier. Le rapport présente une

étude comparative des deux algorithmes. Cette comparaison a été motivée par les résultats de l'évaluation de la performance de la technologie FDMS utilisée par COMDAT et celle du système actuel de commandement et contrôle. Dans cette dernière, COMDAT MSDF n'a pas montré les performances en matière d'association prévues par la théorie.

Executive summary

Performance evaluation within CASE_ATTI of MHT and JVC association algorithms for COMDAT TD

A. Benaskeur, S. Yuen , Z. Triki; DRDC Valcartier TR 2003 – 287; Defence R&D Canada – Valcartier; May 2007.

Defence Research & Development Canada (DRDC) Valcartier is a partner in the Command Decision Aid Technology (COMDAT) TDP. The main part of its contribution consists of i) performing an independent sea trial data analysis to assess the performance of the MSDF technology compared to the legacy Command & Control System (CCS); ii) performing a sensitivity analysis of COMDAT Multi-Sensor Data Fusion (MSDF) parameter sand algorithms, in order to make recommendations for any possible improvements for COMDAT subsequent cycles; and iii) providing scientific advises for MSDF technology to the lead Lab. The current report presents the results of the work performed, at DRDC Valcartier, as a part of the sensitivity analysis of the fusion algorithms used in COMDAT compared to the ones implemented in DRDC Valcartier's Concept Analysis and Simulation Environment for Automatic Target Tracking and Identification (CASE_ATTI) test-bed. This analysis should allow providing recommendations for improvements of the COMDAT MSDF engine. The main objective of this task consists of evaluating a candidate alternative to the Jonker, Volgenant & Castanon (JVC) association algorithm that is used by COMDAT MSDF. This candidate is the Multiple Hypothesis Tracking (MHT) association algorithm, an implemented version of which is available in CASE_ATTI. This report presents a comparison of JVC and MHT algorithms, which was motivated by the results of the previously conducted performance evaluation of COMDAT MSDF and CCS. The latter showed a slight superiority of the CCS over the MSDF in terms of association performance. The herein reported evaluation of the JVC and MHT shows that, even though it is proved theoretically that MHT is the best association algorithm, the presented results reveal no real advantage, with real world data, of MHT over JVC. Nevertheless, the fact that MHT shows no advantage over JVC with real data should be regarded as tentative and needs more verification through additional experimentation. Behaviour of MHT with real world data is not well understood yet. More sensitivity analysis is required to gain a clear idea of how the MHT could work in a practice, and this analysis left a number of questions unanswered. Rather than investigating or envisaging the implementation of new complex algorithms, such a MHT, it would be more judicious and safer to optimize the currently available JVC version. Also, enhancements of other functionalities, such the gating and the estimation, may help increase the performance of the association algorithm.

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Sommaire

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A. Benaskeur, S. Yuen , Z. Triki; DRDC Valcartier TR 2003 – 287; Recherche et développement pour la défence Canada - Valcartier; mai 2007.

Recherche et développement pour la défense Canada (RDDC) – Valcartier est un partenaire clé dans le projet démonstrateur technologique Command Decision Aid Technology (COMDAT). La partie pricipale de la contribution de RDDC Valcartier à COMDAT comprend trois volets : i) la conduite d'une analyse indépendante des données des essais en mer afin de comparer la technologique de Fusion de Données Multi-Sources (FDMS), utilisée par COMDAT, à la technologie utilisée par le système de commandement et contrôle actuel des frégates canadiennes ; ii) réaliser une étude de sensibilité des paramètres et/ou des algorithmes utilisés par FDMS de COMDAT. Cette analyse sert de base pour recommander d'éventuelles améliorations qui s'avéreraient nécessaires ; et enfin iii) prodiguer des conseils scientifiques en matière de FDMS selon les besoins du projet. Ce document présente les résultats du travail effectué dans le cadre de l'analyse de sensibilité des algorithmes utilisés dans COMDAT, comparativement à ceux disponibles dans le banc d'essais Concept Analysis and Simulation Environment for Automatic Target Tracking and Identification (CASE_ATTI) de RDDC Valcartier. Une telle analyse devrait mener à des recommandations pour l'amélioration du système de fusion de données de COMDAT. L'objectif principal de la tâche consignée dans ce document consiste à évaluer les performances d'une solution de rechange à l'algorithme d'association Jonker, Volgenant & Castanon (JVC) utilisé dans COMDAT. Il s'agit de l'algorithme Multiple Hypothesis Tracking (MHT), dont une implantation est disponible dans CASE_ATTI. Le rapport présente une étude comparative des deux algorithmes. Cette comparaison est motivée par les résultats de l'évaluation des performances de la technologie utilisée par COMDAT et le système actuel de commandement et contrôle. Cette étude a montré une légère supériorité du système actuel sur COMDAT, en matière d'association. La comparaison rapportée dans le présent document montre, quant à elle, que, malgré une supériorité théorique prouvée du MHT, les résultats obtenus ne révèlent aucun avantage réel d'une méthode sur l'autre avec des données expérimentales réelles. Dans un tel contexte, le comportement de l'algorithme du MHT est encore mal compris et une analyse plus approfondie est requise afin de statuer sur ses réelles capacités. Il en a été conclu qu'envisager l'implantation d'un tel algorithme dans COMDAT est prématuré, et qu'il serait plus judicieux de consacrer cet effort à l'optimisation de la version déjà disponible de JVC. Un effort serait également nécessaire pour l'amélioration des autres fonctionnalités qui font partie du système de pistage. Une telle amélioration aurait certainement un impact positif sur la qualité de l'association.

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Table of contents

List of figures

List of tables

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Acronyms

AC	Association Correctness
ACD	Average Completeness Deviation
CAR	Correct Assignment Ratio
CASE_ATTI	Concept Analysis and Simulation Environment for Automatic Target Tracking and Identification
C^2	Command and Control
C2IS	Command and Control Information System
CCS	Command & Control System
COMDAT	Command Decision Aids Technology
CH	Completeness History
Cr	Credibility
CSD	Completeness Standard Deviation
DRDC	Defence Research & Development Canada
Er	Error Reduction
FDMS	Fusion des Données Multi-Sources
GCS	Global Credibility Score
GERS	Global Error Reduction Score
HSP	Hard Soft Prediction
JVC	Jonker, Volgenant & Castanon
MHT	Multiple Hypothesis Tracking
LMC	Lockheed Martin Canada
MEAF	Maximum Error Amplification Factor
MERF	Minimal Error Reduction Factor
MOP	Measure of Performance
MSDF	Multi-Sensor Data Fusion
MTP	Maritime Tactical Picture
PAS	Positional Accuracy Statistics
R&D	Research and Development
RDDC	Recherche & Développement pour la Défense Canada
RMSE	Root Mean Square Error
SDCH	Standard Deviation of the Completeness History
TACH	Time Averaging of the Completeness History
TC	Track Continuity (TC)
TDP	Technology Demonstrator Project
TP	Track Purity
VOI	Volume Of Interest
VUE	Volume of Uncertainty Ellipsoid

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1 Introduction

Studies of the Canadian Navy's operational requirements for maritime Command and Control (C^2) in the 2010 time frame have recommended increased emphasis in the areas of data fusion and decision support to the shipboard Command Team. In response to this requirement, Command Decision Aid Technology (COMDAT), a Technology Demonstrator Project (TDP) taking place during the June 2000 to March 2007 time frame, aims to form the basis for defining a Multi-Source Data Fusion (MSDF) capability for the mid-life upgrade to the Command and Control Information System (C2IS) of the Halifax Class frigates. The overall TDP program consists of developing an integrated Maritime Tactical Picture (MTP), which is being achieved through three development cycles. Human Factors Studies taking place in COMDAT will be producing recommendations used in building the human computer interfaces.

Defence Research & Development Canada (DRDC) Valcartier is a partner in the COMDAT project, whose contribution consists of the following tasks:

1. Functional architecture studies;
2. Definition of system Measures Of Performance (MOPs) and Measures Of Effectiveness (MOEs);
3. The application of Model-Based Measures (MBM);
4. Sea trial data analysis to assess the performance of the MSDF technology compared the legacy Command & Control System (CCS).
5. COMDAT MSDF parametric and algorithmic sensitivity analysis. This activity uses the DRDC Valcartier's Concept Analysis and Simulation Environment for Automatic Target Tracking and Identification (CASE_ATTI) testbed [1]. This analysis is aimed to make improvement recommendations for COMDAT Cycle III.
6. Provide scientific advises for MSDF technology.

The work presented id this document concerns the activity #5. This is about the sensitivity analysis, in the CASE_ATTI test-bed, of the fusion algorithms equivalent to the ones used in COMDAT. This analysis is aimed to provide recommendations for the improvement of the COMDAT MSDF engine. This analysis includes a parametric level sensitivity analysis, an algorithmic level sensitivity analysis, and where/when possible a reasoning-path level sensitivity analysis. These three levels of sensitivity analysis are described below

1. **Parametric level sensitivity analysis:** compares COMDAT fusion algorithms equivalent to the ones implemented in CASE_ATTI. Parameter tuning is modified (optimized) to investigate possible improvements. Such an analysis was performed and, so far, the obtained results are not very conclusive. The results are partially documented in [2]. Further work is required for this task.

2. **Algorithmic level sensitivity analysis:** compares COMDAT-like gating, association, and fusion algorithms with CASE_ATTI algorithms that performs similar tasks. Possible improvements to the limitations encountered during the data analysis process are investigated. The work reported in this document falls under this topic. It presents the results of the comparison of the Jonker, Volgenant & Castanon (JVC) association algorithm [3], that is similar to the one used by COMDAT MSDF, with Multiple Hypothesis Tracking (MHT) association algorithm [4] of CASE_ATTI. This comparison was motivated by the results of the performance evaluation [5, 6] of COMDAT MSDF and CCS. This analysis showed a slight superiority of the CCS over the MSDF in terms of association performance[1].

3. **Reasoning-path level sensitivity analysis:** The reasoning path is viewed here as a possible sequence of single functions and processing to achieve a given task. Investigating different reasoning paths, for the fusion system goes further than just the parameter and/or algorithm changes in order to improve the system performance. This includes changing the assumptions, models, etc. Alternative reasoning-paths are proposed to overcome limitations that cannot be handled by parameter tuning and algorithm replacement. Due the time and resource constraints, this task was not performed.

This work was performed during the June–August, 2003 time period.

This report is organized as follows. An overview of the scenarios performed during the Cycle I sea trials, the configuration parameters for the different algorithms used in CASE_ATTI, and the data used are given in Section 3. Section 4 presents the set of MOPs used for the performance evaluation. Section 5 gives the results of this evaluation using the selected MOPs applied to a sub-set of runs. Concluding remarks and recommendation are given in Section 6.

[1]Nonetheless, given the small size of the data sample used, any noticed differences in association performance are not statistically significant. A larger data set is required to confirm the noticed superiority, if there is any. The work presented here aims at finding an alternative to the JVC approach used in COMDAT.

2 Algorithmic Background Information

The foremost difficulty in multiple-target tracking applications is to resolve the source data origin uncertainty issue. That is, one has to determine from which perceived target, if any, each individual input data report element originated before the kinematic and identification fusion processes can be performed with this data. The correlation procedure, broadly known as data association, thus links input data reports from single or multiple sources to perceived individual physical platforms or entities (such as aircraft, missiles, ships, etc.). The association may be based upon kinematic parameters (*i.e.*, position, velocity, etc.), non-kinematic target attributes (*e.g.*, emitter characteristics, target signature features, etc.), or both simultaneously [7].

Data association process contains several steps, the most critical of which is the data assignment. In general, this step takes the output of the gating function and makes the final assignments. It represents a more formal procedure than gating for pairing input data to system tracks; alone, data assignment is sufficient to perform the entire data association task.

2.1 Data Assignment

In any multiple-target tracking application where the actual number of true targets in the environment is unknown a priori, there is, at any given time, a number of plausible ways to partition the source data into tracks and false targets (false alarms). The objective of the assignment task is to relate each data element received to a number of possible sets of data, each one representing a hypothesis to explain the origin of the report [7].

Two data assignment algorithms, the Multiple Hypothesis Tracking (MHT) and the Jonker-Volgenant-Castanon (JVC) approaches, are discussed next and compared throughout this report. More background information on the MHT and JVC algorithms can be found in the open literature [8, 9, 10, 11], and won't be presented in this document. The more specific variants and detailed characteristics of the algorithms used in this comparison are well documented through the CASE_ATTI-related publications [12, 13, 1, 14, 7, 15, 16] and documentations provided with the distribution CD.

2.1.1 MHT

The Multiple Hypothesis Tracking (MHT) algorithm [4] uses the knowledge that a report exists and compute the probability that this report can be associated to an existing system track, to a new track, or to a false alarm. The MHT algorithm intrinsically possesses the desirable feature of multiple-scan correlation. The basic philosophy behind the MHT is that there are many situations that occur in the tracking of targets where there is ambiguous information. Rather than using some arbitrary criteria to make a decision as to how to remove the ambiguity and resolve the difficult assignments immediately, it is more optimal to wait until more input data elements have been collected and there is enough information data available to substantiate or refute these assignments and thus postponed the final decision as to the correct one. With the MHT approach, all possibilities concerning the origin of received source data are enumerated as alternative hypotheses. These hypotheses will, in general, contain some groupings of input data elements into tracks and the identification of other elements to be false alarms. The probability of each hypothesis is computed and, ideally, all hypotheses are maintained and re-evaluated when subsequent source data are received. An hypothesis whose probability is increased correspond to the case in which subsequent reports increase the likelihood of these data associations [7]. While it takes time for the system to select the correct hypothesis, if a decision is required earlier, the highest probability hypothesis would be used, and under no circumstances would this hypothesis ever be any worse than what any other algorithm would provide. The only real disadvantage of the MHT algorithm over the others is its processing load. This is discussed in the next subsection.

The computational requirements necessitated by the ability to retain multiple interpretations of the situation represent the main drawback of the MHT algorithm (and also the principal deterrent to its widespread usage). Allowing for multiple targets and for new track initiation can lead to complex bookkeeping and to a rapid growth in the number of hypotheses formed. Without appropriate control mechanisms, the number of hypotheses is exponentially increasing with time [7]. Since it is impractical to maintain all hypotheses, a suboptimal implementation which includes mechanisms for keeping the number of hypotheses down must be used. Indeed, the success of an efficient MHT implementation is primarily dependent on

1. the development of a scheme which can effectively limit the number of hypotheses formed,

2. the development of methods of reducing the large number of hypotheses ultimately formed to a manageable number of hypotheses, and,

3. the construction of an efficient data structure to represent the hypothesis tree and track data information.

Clustering is a practical approach that can be combined with MHT to reduce its computational requirements. Clustering is the process of dividing the entire set of system tracks and input data elements into independent groups (or clusters). Instead of solving one large problem, a number of smaller problems are solved in parallel.

2.1.2 JVC

The JVC (Jonker-Volgenant-Castanon) is one the set algorithms that optimally solve (under constraints) the 2-D assignment algorithm. The JVC algorithm solves this constrained optimization into two stages. The first stage ensures the feasibility of the assignment problem by an appropriate conditioning of the assignment matrix and is similar to the auction algorithm. The second stage is similar to a sparse version of the Munkres algorithm. It considers only the finite values of the assignment matrix (prohibited associations are represented in the assignment matrix as very large values). In addition to ensuring the feasibility of the assignment problem, the initialization phase of the algorithm provides a very good conditioning for the paths search and makes the JVC faster than the other shortest path algorithms. By an appropriate increase of the overhead, the algorithm reduces the required computations in the search step and by the same way the overall computation time.

Besides data association, the filtering is also very important in tracking system. Nevertheless, tracking performance with even the best designed filter may become very degraded in the presence of miscorrelation. The effects of miscorrelation can completely invalidate the the used filter and lead to divergence. The Interacting Multiple Model (IMM)-based filtering technique, used by both COMDAT MSDF and CASE_ATTI to overcome the limitations of dynamics modeling, is briefly discussed for completeness.

2.2 IMM

Some practical model of target motion is assumed for the design of the Kalman filter. This target kinematics model is generally simple (such as a straight-line path, a slow turn, a sharp turn, etc.) and assumed to be described by well-known physical laws (*e.g.*, ballistic laws, etc.). The target dynamics are modeled through the use of continuous random variables statistically described by known parameters. The Kalman filter will provide optimum estimates of target position and velocity (*i.e.*, it will minimize the mean-squared error) only if the underlying target model is correct. Unpredictable changes to the assumed target motion model are called maneuvers. Any mismatch, during a maneuver, between the actual kinematics behavior of a target and the motion model assumed for filter design can completely degrade the performance of the estimation technique (*i.e.*, mean tracking errors will develop).

At the moment when the target maneuver begins, there may be a step discontinuity in acceleration. The target acceleration can be well modeled as a continuous random variable, both before and after the maneuver event, but the step acceleration input is not efficiently handled by the continuous model. Unless this type of acceleration is accounted for, the resulting time lag between the initiation and the detection of the acceleration change can lead to track loss. In the presence of a high speed maneuvering target, with noise and clutter, it is critical to be able to detect the maneuver and continue tracking the target in its new course as quickly as possible. Using different filtering techniques, there are various approaches proposed in the literature for handling target maneuvers. The resulting filter is often called an adaptive Kalman filter. One of the widely used adaptive Kalman filtering approach that gives very good tracking performance is based on the use of Interacting Multiple Model (IMM) Kalman filters.

In the IMM approach, the state estimate is computed at time k under each possible current model using r filters, with each filter using a different combination of the model-conditioned estimates (*i.e.*, mixed initial condition). The approximation is that the past through $k-1$ is summarized by r model-conditioned estimates and covariances. The input to the filter matched to model j is obtained from an interaction of the r filters, which consists of the mixing of the estimates at time $k-1$ with the weights μ_j (probabilities) called the mixing probabilities.

2.3 Parameters

The different parameters and algorithms used for the tuning and the optimization of the performance of CASE_ATTI are list below.

1. **Gating:** uses ellipsoidal gating, with two parameters to tune
   (a) Gating threshold (ellipse area)
   (b) Time aligner's process noise, for manoeuvring targets
   (c) Maximum velocity
2. **Assignation:** uses MHT (with and without clustering) and JVC. The following parameters were used for the optimization
   (a) Number of hypotheses for the MHT tree
   (b) Number of best nodes to keep for MHT tree
   (c) Time aligner's process noise for manoeuvring targets
3. **Filtering:** uses Interactive Multiple Model (IMM) Kalman Filter [17] with following parameters
   (a) Number of sub-filters
   (b) Process noise attributed to the different sub-filters
4. **Track Management**: uses the following parameter
   (a) Track confirmation. To confirm a track, a N number of hits out of a M number of attempts are required. The default value in CASE_ATTI is 3 out of 5. However, that is not necessarily a suitable value that give good performance, thus the value is adapted to each run.
5. **Output Manager**
   (a) JVC: Basic output manager with all confirmed track output strategy
   (b) MHT: Hard Soft Prediction (HSP) output manager with newly confirmed hard decided track output strategy

3 Scenarios, data generation, and algorithm behavior

The data used by DRDC Valcartier for the herein reported algorithmic analysis is the same as the one used in the previously performed sea trial data analysis [5, 6]. This data set was provided to DRDC Valcartier by Lockheed Martin Canada (LMC), through DRDC Atlantic, in a confidential CD labelled “MOPs MSDF, Volume C.1”. DRDC Valcartier received two CDs containing COMDAT sea trial data. The two data sets present small differences, due mainly to the time reference problem. Therefore, the performed comparison is based on the same COMDAT Cycle I sea trial scenarios. Note that the available COMDAT data set includes radar data (both SPS-49 and SG-150), IFF data (both SPS-49 and SG-150) and ESM data. For the purpose of this analysis, only the radar data was processed.

3.1 Methodology

The approach adopted to compare JVC to MHT is to use implementations of both algorithms within CASE_ATTI environment. COMDAT Cycle I sea trial data is then processed through both sets of algorithms. Also, it is worth noting that the implementation of JVC/IMM algorithms within CASE_ATTI is different from their implementation within COMDAT, even though the approach remains the same. This approach is the best way to compare the association algorithms because it allowed other data fusion system components (gating, estimation, track maintenance,...) to be held constant.

The ground truth information and the sensor reports are used as inputs to CASE_ATTI. In order to keep this document UNCLASSIFIED, no information from the sensor will be presented. Only the track information generated by CASE_ATTI will be used for the comparison. During the preliminary experimentations with different runs, it was realized that some of the data, namely the contacts and the ground truth, are unsynchronized and biased. Also, some of the ground truth data are missing from the provided data CD. Therefore, appropriate adjustments were brought to apply correction where necessary. However, nothing could be done for the missing data, thus some of the runs are not analyzed. This concerns mainly runs 5, 6 and 10. Also, using CASE_ATTI test-bed for comparison implies the conversion of COMDAT ground truth and measured data into CASE_ATTI ground truth and measured data format. Modifications were brought to CASE_ATTI to render this conversion possible. What also was retained from the experimentations performed is that the implementation of MHT in CASE_ATTI does not allow tracking when only the SPS-49 radar system reports. MHT will work correctly only where one has both SPS-49 and SG-150 reports. Therefore, only such sections are used for the comparison of JVC and MHT. Also, the clustering within MHT does not necessarily yield a good performance for most of the runs. A poor clustering performance will increase the computation burden due the overhead required by the cluster management (merge and split) operations.

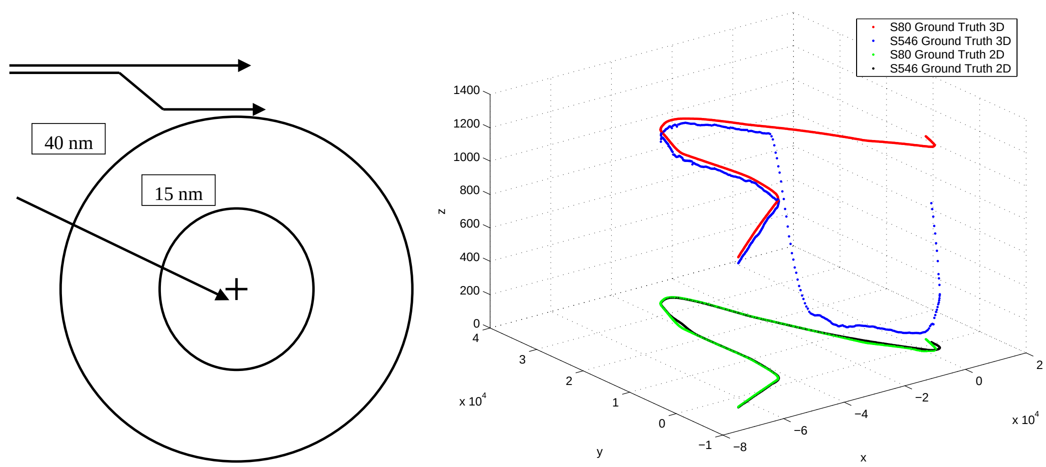
3.2 Sea Trials

The sea trials were conducted during Spring 2001 based on 13 scenarios. These scenarios are briefly described in the current section, and the corresponding ground truth information presented. This information and the sensor reports are used as inputs to the CASE_ATTI test-bed. The following sections give a summary of the scenarios, data, run properties, and the algorithm behaviour. Note that each one of these runs has been experimented with different parameters and algorithms in CASE_ATTI. In total, more than 700 experimentations were conducted.

Tables 1 to 7 below give, for both JVC and MHT, the combination of parameters that gave the best performance for the considered runs. Note that, during the algorithm-tuning phase, all the listed parameters were varied. Given the very limited time available to perform the analysis, no procedure was developed; rather, an ad hoc approach was used. Also, the parameters were optimized for each run separately.

3.2.1 Run 1

The scenario of **Run 1** is described on Figure 1. Both aircraft begin flying as close together as safety allows, on the same course, elevation and speed. At $15nm$ one aircraft descends to $200ft.$, at $5nm$ the run ends.



(a) Scenario (b) Ground Truth data

Figure 1: *Run 1*

Algorithm behavior

Tracking of both targets was possible with JVC during the whole run. For the IMM, four filters were used instead of three. The latter configuration makes the system loose the targets. It was impossible to track both targets during the whole run with the MHT. One track is created at the beginning of the run and remains until the end, while the other track is only created at the end of the run. MHT without clustering often causes the re-initialization (out of hypotheses) of the tracking. Therefore only the MHT with clustering is considered for this run. Tracking of both targets was also possible, for **Run 1B**, with

JVC during the whole run. Tracking of both targets was possible during the whole run with MHT using an IMM (with three filters). The clustering is not used for this run because:

1. it takes too long time to run (more than an hour for one step), or
2. it reduces the quality of tracks compared to the MHT without clustering.

Parameters	**Values JVC**	**Value MHT**
Maximum Velocity	500 m/s	500 m/s
Coordinate Converter	Standard mode	Standard mode
Gating	Ellipsoidal Gate	Ellipsoidal Gate
Gate Probability	0.999	0.999
Gate Process Noise	400	400
Filter	IMM 4	IMM 4
IMM Process Noise	5, 100, 200, 400	5, 100, 200, 400
M out Of N System Track	3/10	3/5
Assignation	JVCNN	MHT Clustering
JVCNN Process Noise	400.0	
MHT Process Noise		400.0
Mode of pruning		Best node
Number of best node to keep		5
Number of hypotheses		100
SPS49 Scan_RPM & Scan_bearing_division	12 & 4	12 & 4
SG150 Scan_RPM & Scan_bearing_division	60 & 32	60 & 32
Output	Basic Output	HSP Output

Table 1: *Parameter and values of Run 1*

3.2.2 Run 2

The scenario of **Run 2** is described on Figure 2. Both aircraft begin flying as close together as safety allows, on the same course, elevation and speed. At 15nm one aircraft will accelerate to 250mph. At 5nm the run ends.

Algorithm behaviour

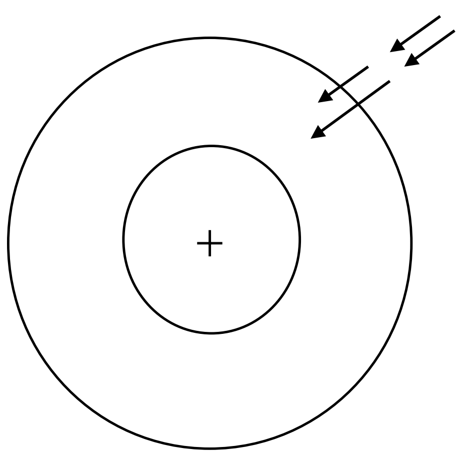
Tracking of both targets was possible with JVC during the whole run. Tracking of both targets was possible only on a portion of the run with MHT. Some ad hoc tunings allow tracking both targets during the whole run (requires more investigation). The clustering is not used since it reduces the quality of tracks.

3.2.3 Run 3

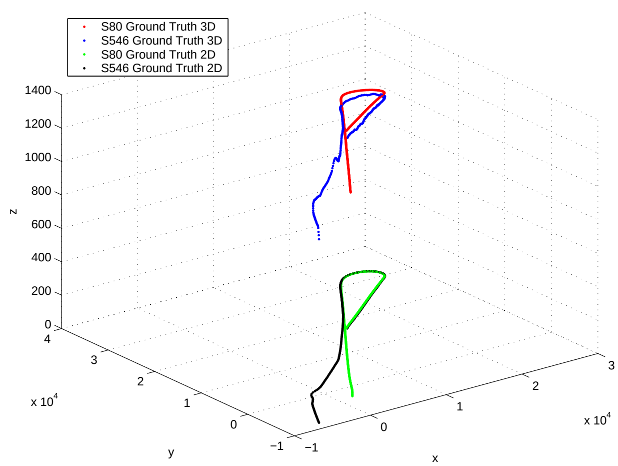
The scenario of **Run 3** is described on Figure 3. The two aircraft fly the same profile, but following opposite S shape, perform a mean line of advance toward the ship, while each

Parameters	Values JVC	Value MHT
Maximum Velocity	500 m/s	500 m/s
Coordinate Converter	Standard mode	Standard mode
Gating	Ellipsoidal Gate	Ellipsoidal Gate
Gate Probability	0.999	0.999
Gate Process Noise	50	50
Filter	IMM 4	IMM 3
IMM Process Noise	5, 10, 30, 50	5, 25, 50
M out Of N System Track	3/10	3/5
Assignation	JVCNN	MHT
JVCNN Process Noise	50.0	
MHT Process Noise		50.0
Mode of pruning		Best node
Number of best node to keep		30
Number of hypotheses		150
SPS49 Scan_RPM & Scan_bearing_division	12 & 4	12 & 4
SG150 Scan_RPM & Scan_bearing_division	60 & 32	60 & 32
Output	Basic Output	HSP Output

Table 2: *Parameter values for Run 1b*



(a) Scenario



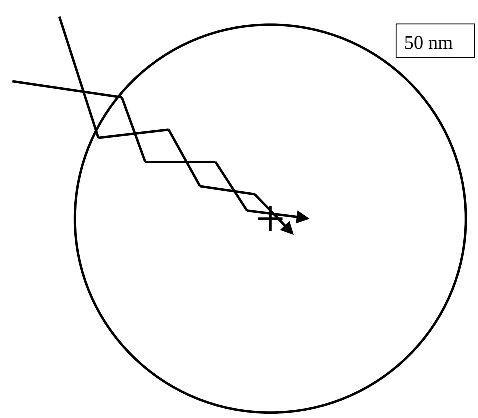
(b) Ground Truth data

Figure 2: *Run 2*

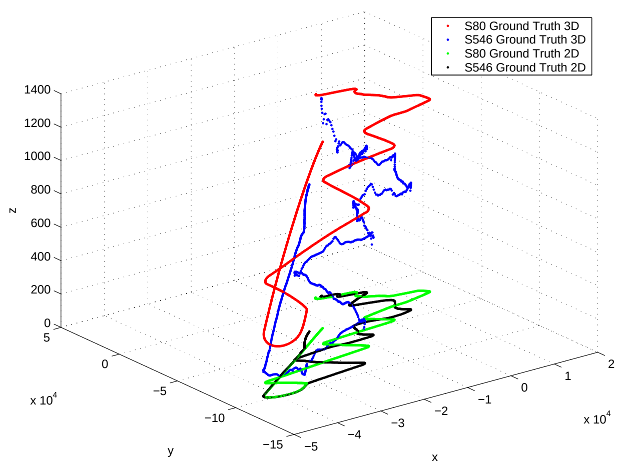
Parameters	Values JVC	Value MHT
Maximum Velocity	500 m/s	500 m/s
Coordinate Converter	Standard mode	Standard mode
Gating	Ellipsoidal Gate	Ellipsoidal Gate
Gate Probability	0.999	0.999
Gate Process Noise	75.0	75.0
Filter	IMM 3	IMM 3
IMM Process Noise	5, 20, 75	5, 20, 75
M out Of N System Track	3/10	3/5
Assignation	JVCNN	MHT
JVCNN Process Noise	75.0	
MHT Process Noise		75.0
Mode of pruning		Best node
Number of best node to keep		5
Number of hypotheses		100
SPS49 Scan_RPM & Scan_bearing_division	12 & 4	12 & 4
SG150 Scan_RPM & Scan_bearing_division	60 & 32	60 & 32
Output	Basic Output	HSP Output

Table 3: *Parameter values for Run 2*

aircraft weaves across the mean line of advance. The maximum separation between aircraft is initially $3nm$. The maximum separation diminishes as it approaches the ship (*i.e.*, $3nm$ at $60nm$ range, 1.5 at $30nm$ range, etc.). Safety can be assured by altitude separation.



(a) Scenario



(b) Ground Truth data

Figure 3: *Run 3*

Algorithm behaviour

Tracking of both targets, using JVC, was possible during the whole run, but one track has split into two tracks. It was impossible to track both targets during the whole run, using MHT, because most of time there were only SPS-49 reports. The clustering is not used for this run because it reduces the quality of tracks.

Parameters	**Values JVC**	**Values MHT**
Maximum Velocity	500 m/s	500 m/s
Coordinate Converter	Standard mode	Standard mode
Gating	Ellipsoidal Gate	Ellipsoidal Gate
Gate Probability	0.999	0.999
Gate Process Noise	500.0	500.0
Filter	IMM 4	IMM 4
IMM Process Noise	5, 200, 400, 500	5, 200, 400, 500
M out Of N System Track	3/15	3/5
Assignation	JVCNN	MHT
JVCNN Process Noise	500.0	
MHT Process Noise		500.0
Mode of pruning		Best node
Number of best node to keep		10
Number of hypotheses		50
SPS49 Scan_RPM & Scan_bearing_division	12 & 4	12 & 4
SG150 Scan_RPM & Scan_bearing_division	60 & 32	60 & 32
Output	Basic Output	HSP Output

Table 4: *Parameter values of Run 3*

3.2.4 Run 4

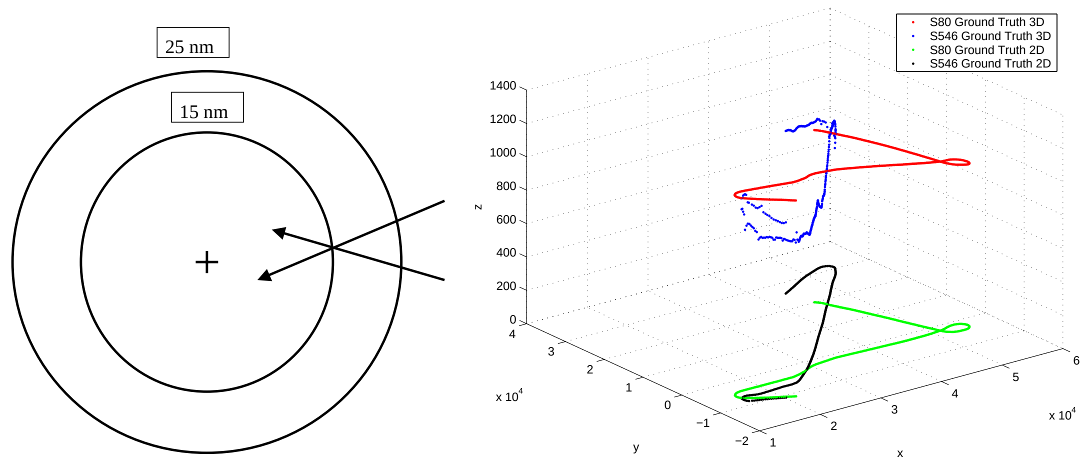
For the scenario of **Run 4** (see Figure 4), the two aircraft begin by flying towards one another at a shallow crossing angle. At $15nm$ they cross, as close to one another as safety allows, separate and continue to fly past the ship.

Algorithm behaviour

Tracking of both targets, using JVC, was possible during the whole run. Tracking, using MHT, was possible whenever the SG-150 starts to report. The clustering is not used because it reduces the quality of tracks, and may, in some situations, not produce tracks at all.

3.2.5 Run 5

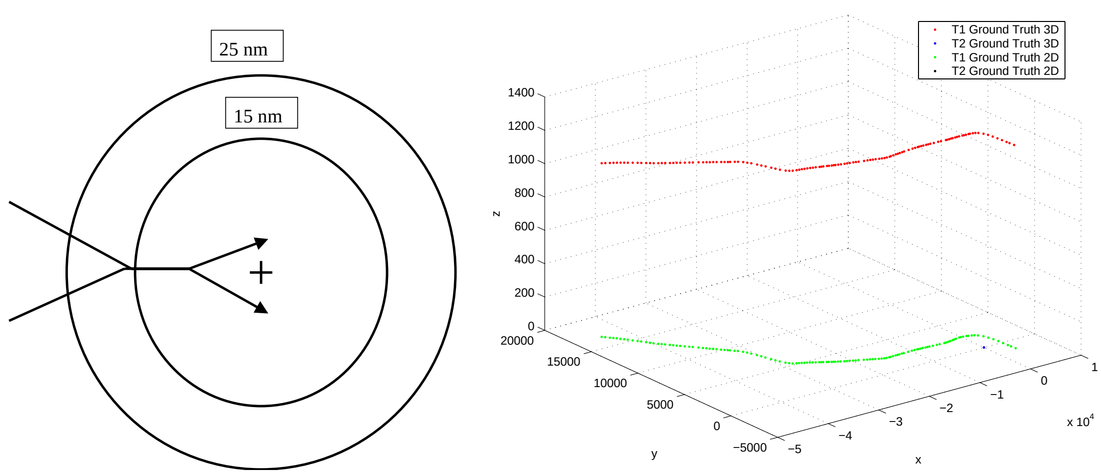
Figure 5 shows **Run 5** that starts with a distance separation of $3miles$. Both aircraft fly towards each other at an acute angle of approach. They merge at $15nm$ from the ship and



(a) Scenario (b) Ground Truth data

Figure 4: *Run 4*

stay as close as safety allows for $5nm$. At this point ($10nm$), they separate and pass the ship on either side. This Run uses all IFF settings.



(a) Scenario (b) Ground Truth data

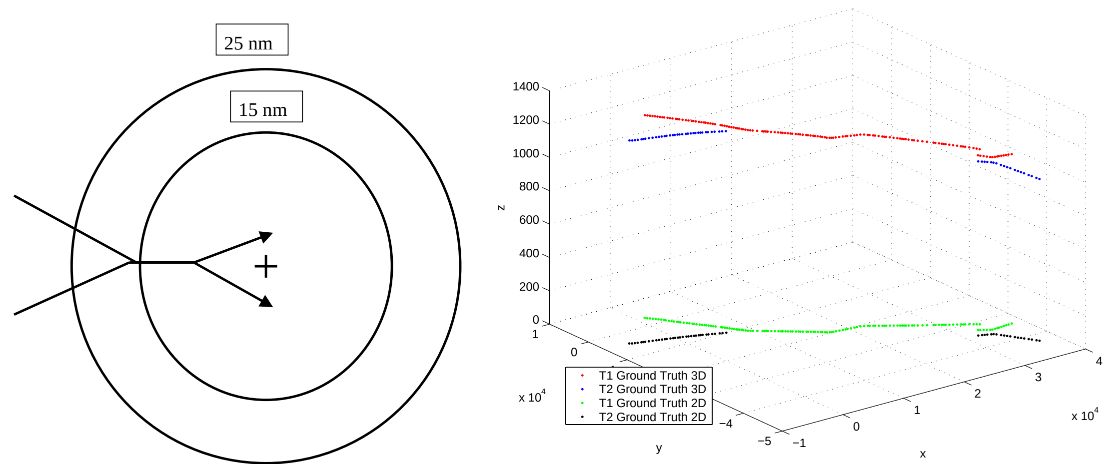
Figure 5: *Run 5*

Algorithm behaviour

This run was not analyzed, since the ground truth information is incomplete and data are not synchronized.

3.2.6 Run 6

Run 6 (see Figure 6) starts with a distance separation of $3 miles$. Both aircraft fly towards each other at an acute angle of approach. They merge at $15nm$ from the ship and stay as close as safety allows for $5nm$. At this point ($10nm$), they separate and pass the ship on either side. This Run is conducted without IFF settings.



(a) Scenario (b) Ground Truth data

Figure 6: *Run 6*

Algorithm behaviour

As for the Run 5, this run was not analyzed, since the ground truth information is incomplete and data are not synchronized.

3.2.7 Runs 7 & 8

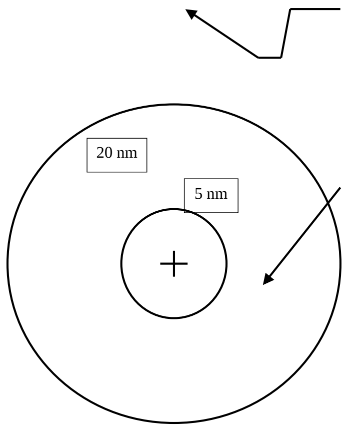
During **Run 7**, as shown on Figure 7 (a), aircraft begins at an altitude of $2000ft$. At $5nm$, aircraft descends rapidly to $200ft$. Once past the ship the aircraft is free to return to altitude. For **Run 8**, shown on Figure 7 (b), aircraft fly towards ship. At $5nm$, aircraft performs a $90°$ turn, either left or right

Algorithm behaviour

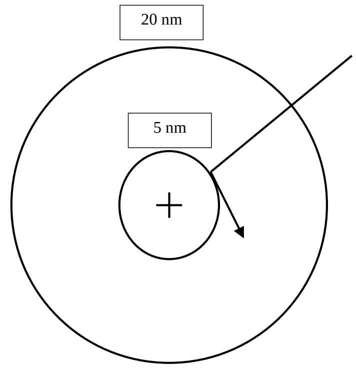
Tracking of both targets, using JVC, was possible during the whole run. Tracking of both targets was possible during the whole run using MHT. Clustering works correctly, the track quality is comparable to the one given by MHT without clustering.

3.2.8 Run 9

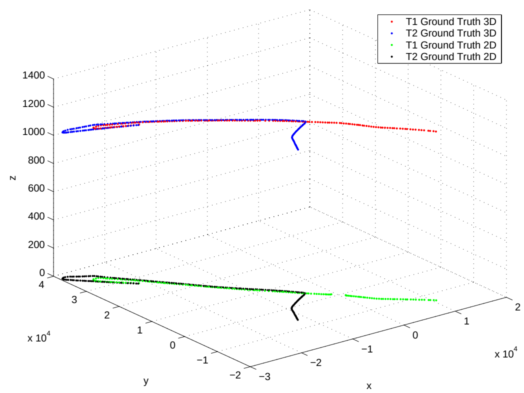
For **Run 9** (see Figure 8), both aircraft are to fly one complete circle around the ship at a range of $20nm$. One aircraft flies in clockwise direction, the other flies counter clockwise.



(a) Scenario 7



(b) Scenario 8



(c) Ground Truth data

Figure 7: *Runs 7 & 8*

Algorithm behaviour

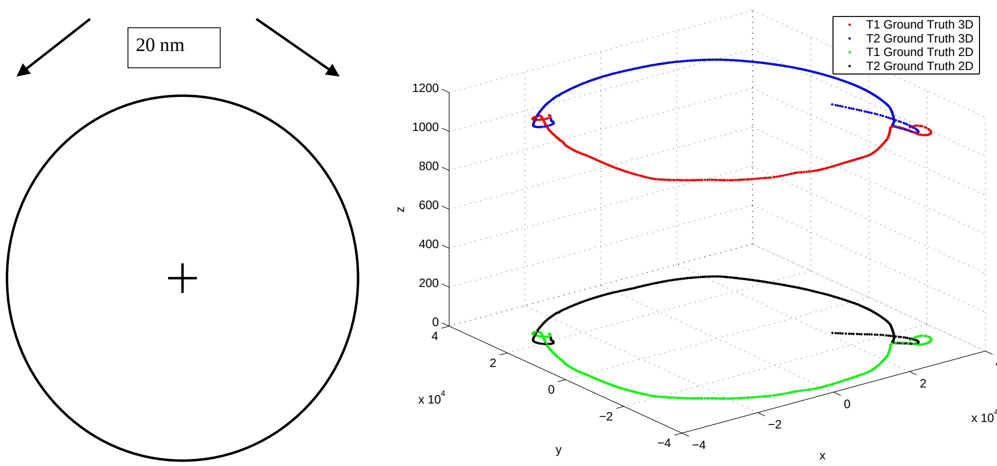
Tracking, using JVC, of both targets was possible during the whole run. Tracking of both targets during the whole run was also possible using MHT.

3.2.9 Run 10

As shown Figure 9, two groups of targets approach the ownship, in **Run 10**. Group 1, formed by T-33 Alpha, Bravo and Charlie and Lear Jet Alpha, approaches on a direct line of constant bearing. Lear jet Bravo approaches the ownship on a curved approach. As Lear Jet Bravo crosses over the path of the other group, T-33 Alpha and Bravo should curve to the same bearing and approach pattern as the Lear jet Bravo.

Parameters	Values JVC	Values MHT	Values MHTC
Maximum Velocity	500 m/s	500 m/s	500 m/s
Coordinate Converter mode	Standard	Standard	Standard
Gating	Ellipsoidal	Ellipsoidal	Ellipsoidal
Gate Probability	0.999	0.999	0.999
Gate Process Noise	800.0	800.0	800.0
Filter	IMM 3	IMM 3	IMM 3
IMM Process Noise	5, 400, 800	5, 400, 800	5, 400, 800
M out Of N System Track	3/5	3/5	3/5
Assignation	JVCNN	MHT	MHT (Clust.)
JVCNN Process Noise	800.0		
MHT Process Noise		800.0	800.0
Mode of pruning		Best node	Best node
Number of best node to keep		7	3
Number of hypotheses		100	20
SPS49 Scan RPM & Bearing division	12 & 4	12 & 4	12 & 4
SG150 Scan RPM & Bearing division	60 & 32	60 & 32	60 & 32
Output	Basic	HSP	HSP

Table 5: *Parameter values for Run 7&8*



(a) Scenario (b) Ground Truth data

Figure 8: *Run 9*

Algorithm behaviour

This run was not analyzed, since the ground truth information is incomplete and data are not synchronized.

Parameters	Values JVC	Values MHT
Maximum Velocity	500 m/s	500 m/s
Coordinate Converter	Standard mode	Standard mode
Gating	Ellipsoidal Gate	Ellipsoidal Gate
Gate Probability	0.999	0.999
Gate Process Noise	50.0	240
Filter	IMM 3	IMM 3
IMM Process Noise	5, 160, 240	5, 160, 240
M out Of N System Track	3/5	3/5
Assignation	JVCNN	MHT
JVCNN Process Noise	240.0	
MHT Process Noise		240.0
Mode of pruning		Depth control
Number of level to keep		5
Number of hypotheses		100
SPS49 Scan RPM & Bearing division	12 & 4	12 & 4
SG150 Scan RPM & Bearing division	60 & 32	60 & 32
Output	Basic	HSP

Table 6: *Parameter values for Run 9*

3.2.10 Run 11

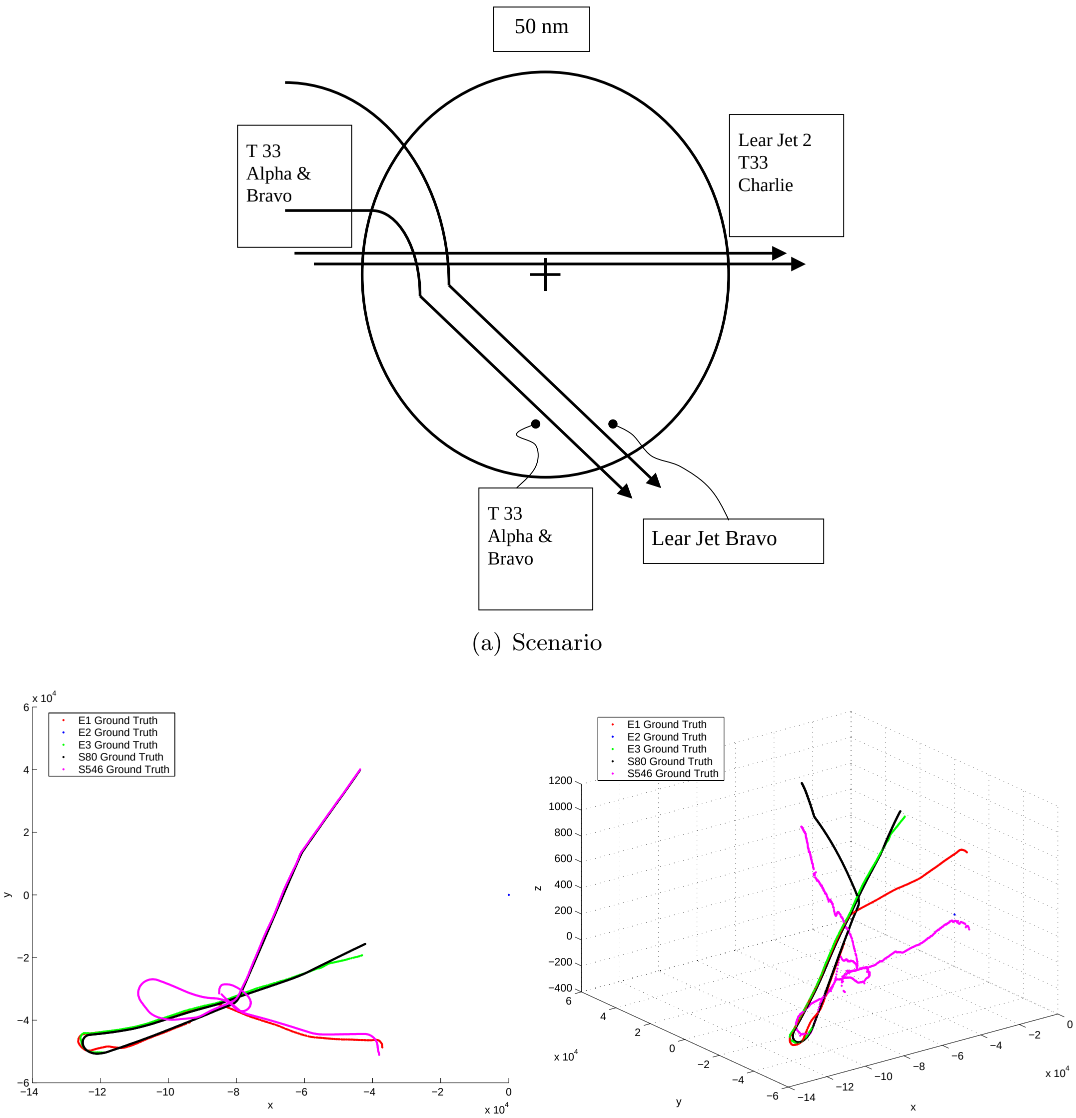
During **Run 11** (see Figure 10), four targets approach the ownship, starting with T-33 Alpha on the left, the next is Lear Jet Alpha, T-33 Bravo and then Lear Jet Bravo. Two outer aircraft cross over and then continue on the same course as opposite track. Have the two inner aircraft cross over and then continue on the same course as the opposite track. T-33 Charlie flies in a reciprocal healing from the other aircraft. Once T-33 Charlie has passed over the ownship, it may turn and proceed to base.

Algorithm behaviour

The system is able to track with JVC and an IMM (4 filters). Tracks are only clear from the middle of the run. It was hard to obtain clear tracks from SPS-49 reports only. Tracking, using MHT, was possible whenever the SG-150 starts reporting. The clustering is not used here, because it produces tracks with lower quality than MHT without clustering. In some situations, it can even not produce tracks at all.

3.2.11 Run 12 & 13

For **Run 12**, shown on Figure 11 (a), aircraft are to fly a straight run in from $60nm$, overhead ship and continue out to $60nm$. During **Run 13** (see Figure 11 (b)), the aircraft initially flies towards the ship. At $50nm$ from the ship, it alters course to left by approximately $45°$. After $30 - 45sec$, it returns to heading towards ship. When $20nm$ from



(a) Scenario

(b) 2D Ground Truth

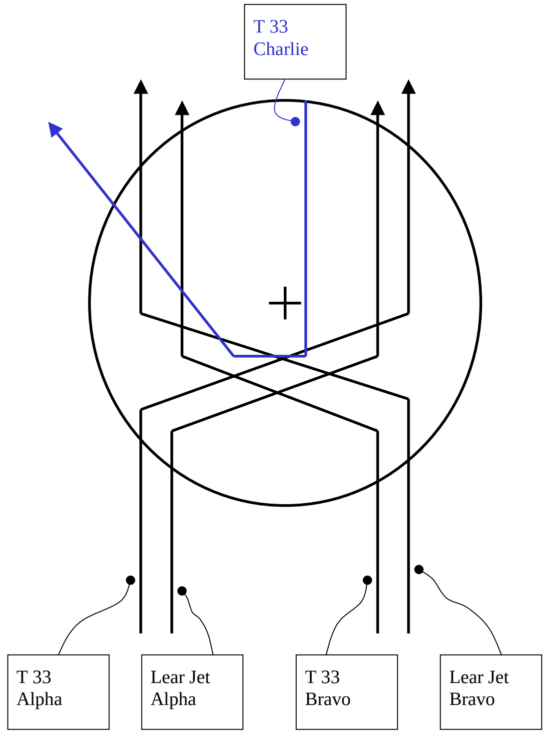
(c) 3D Ground Truth

Figure 9: *Run 10*

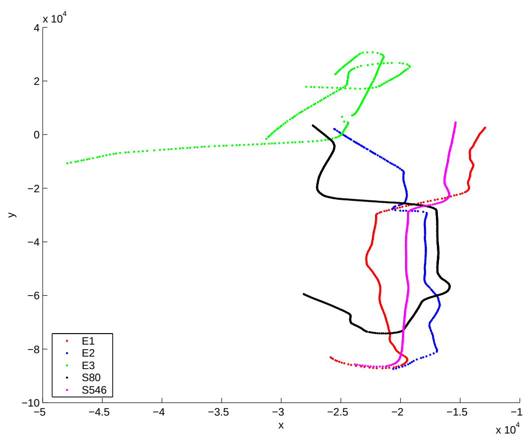
ship, it alters course to the right by approximately 45°. Again, it maintains this course for $30 - 45sec$ and then resumes a course which over tops the ship, and continues outbound to $60nm$.

Algorithm behaviour

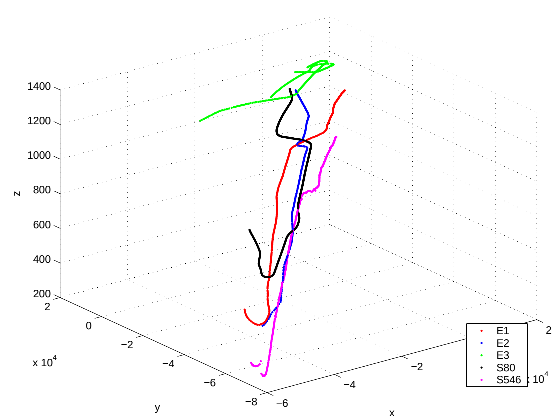
The system is able to track all targets during the whole run using JVC. With the IMM (3 filters), the system adds some false alarms into the track at the end of the run. With MHT, all targets are tracked during the whole run. This concerns the clustered MHT, since MHT



(a) Scenario

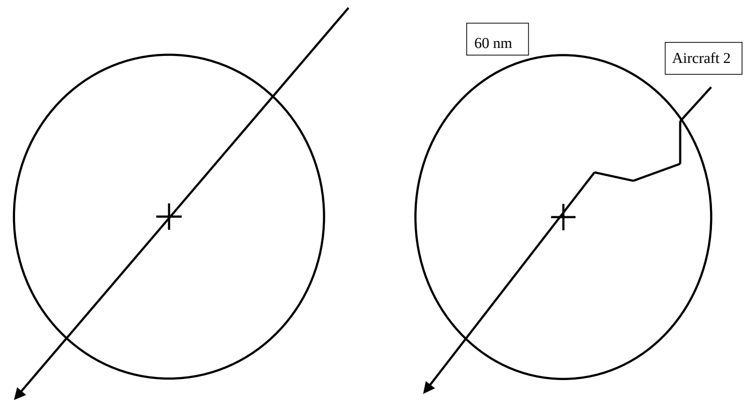


(b) 2D Ground Truth

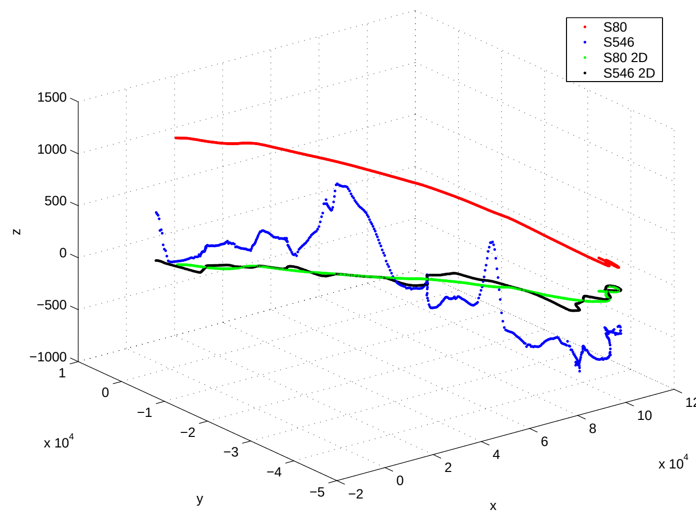


(c) 3D Ground Truth

Figure 10: *Run 11*



(a) Scenario 12 (b) Scenario 13



(c) Ground Truth data

Figure 11: *Runs 12 & 13*

without clustering did not work.

3.3 Summary

Table 8 summarizes the different scenarios performed during the sea trials and their objectives. Besides runs 5, 6 and 10 that are not analyzed because of the missing ground truth information, runs 4 and 11 will also not be analyzed. The reason is that the computation of the association MOPs is not possible due to the data incompleteness. Decision was made not to include the results of the estimation MOPs for these runs as well.

In most runs, the implementation of MHT in CASE_ATTI does not allow tracking when only the SPS-49 radar system reports. MHT worked correctly only where one has both

Parameters	Values JVC	Value MHT
Maximum Velocity	500 m/s	500 m/s
Coordinate Converter	Standard mode	Standard mode
Gating	Ellipsoidal Gate	Ellipsoidal Gate
Gate Probability	0.9999	0.999
Gate Process Noise	500.0	200.0
Filter	IMM 3	IMM 3
IMM Process Noise	5, 250, 500	5,100,200
M out Of N System Track	3/12	3/5
Assignation	JVCNN	MHT Clustering
JVCNN Process Noise	500.0	
MHT Process Noise		200.0
Mode of pruning		Depth control
Number of Level to keep		3
Number of hypotheses		200
SPS49 Scan RPM & Bearing division	12 & 4	12 & 4
SG150 Scan RPM & Bearing division	60 & 32	60 & 32
Output	Basic	HSP

Table 7: *Parameter values for Runs 12 & 13*

SPS-49 and SG-150 reports. Also, the clustering within MHT does not necessarily yield a good performance for most of the runs. In a few runs (1, 12&13) the use of clustering, in combination with MTH, provided a noticeable benefit, while in others (runs 1B, 2, 3, 4, 11) clustering resulted in lower quality tracks or prevented tracking. A poor clustering performance increased the computation burden due the overhead required by the cluster management (merge and split) operations.

Run	Objective	Targets	Type of Targets	Range	Altitude	Speed
01	Separation	S80, S546	Lear Jet	40 nm	4000 ft	250 mph
02	Separation	S80, S546	Lear Jet	40 nm	4000 ft	200 mph
03	Accuracy	S80, S546	Lear Jet	50 nm	4000 ft	250 mph
04	Crossing	S80, S546	Lear Jet	25 nm	4000 ft	250 mph
05	Merging	T1, T2	T-33	25 nm	4000 ft	250 mph
06	Merging	T1, T2	T-33	25 nm	4000 ft	250 mph
07	High Dive	T1	T-33	20 nm	2000 ft	250 mph
08	Sharp Turn	T2	T-33	20 nm	2000 ft	250 mph
09	Radial	T1, T2	T-33	20 nm	4000 ft	250 mph
10	Track crossing and maintaining ID	S80, S546, E1, E2, E3	2 Lear Jets, 3 T-33	40 nm	—	250 mph
11	Track crossing and maintaining ID	S80, S546, E1, E2, E3	2 Lear Jets, 3 T-33	40 nm	—	250 mph
12	SPS49/SG150 Hand Over	S80	Lear Jet	60 nm	4000 ft	250 mph
13	SPS49/SG150 Hand Over	S546	Lear Jet	60 nm	4000 ft	250 mph

Table 8: *Summary of sea trial scenarios*

4 Measures of Performance

In order to show any possible advantage (or disadvantage) of the Multiple Hypothesis Tracking (MHT) association algorithm [4] over the Jonker, Volgenant & Castanon (JVC) algorithm [3], a set of Measures of Performance (MOPs) was selected. These MOPs will be divided into two main classes, namely, the **association** MOPs and the **estimation** MOPs.

Since the MHT and JVC are association algorithms, the association MOPs, that include Track Purity (TP), Correct Assignment Ratio (CAR), Association Correctness (AC) and Average Completeness Deviation (ACD), will serve for the primary comparison. The estimation MOPs, that include the Credibility (Cr) and the Error Reduction (Er), will only provide an insight on how association algorithms affect the performance of the estimation process.

This section gives the list of the MOPs that were initially used for the comparison of the two algorithms. This list represents a sub-set of the MOPs used for sea trial data analysis [5]. Most of those MOPs are based on the confusion matrix that is defined as follows,

		Objects			
		$\boldsymbol{O}_1$	$\boldsymbol{O}_2$		$\boldsymbol{O}_M$
		C_{01}	C_{02}	$\cdots$	C_{0M}
	$\boldsymbol{T}_1$	C_{11}	C_{12}	$\cdots$	C_{1M}
Tracks	$\boldsymbol{T}_2$	C_{21}	C_{22}	$\cdots$	C_{2M}
	$\vdots$	$\vdots$	$\vdots$		$\vdots$
	$\boldsymbol{T}_N$	C_{N1}	C_{N2}	$\cdots$	C_{NM}

where the elements C_{ij} are the number of reports originating from object j and assigned to track i. The elements C_{0j} are the reports originating from object j and not assigned to any track.

4.1 Track Purity

Track Purity assesses the percentage of correctly associated measurements in a given track, and so evaluates the association (and indirectly the tracking) performance. The "purity" of the track T_j is defined as

$$TP(t_j) = \left[\sum_{i=1}^{a} C_{ji} \right]^{-1} \max_{1 \le i \le a} C_{ji} \tag{4.1}$$

where C_{ji} is the number of the reports originating from the ground truth platform g_i assigned to track t_j, and a is the number of the ground truth platforms in the scenario. The calculated MOP, in this work, is the Weighted Average Track Purity (WATP), a statistic of Track Purity calculated over all tracks and ground truth objects.

$$TP = \left[\sum_{j=1}^{b} \sum_{i=1}^{a} C_{ji} \right]^{-1} \sum_{j=1}^{b} \max_{i} C_{ji} \tag{4.2}$$

where b is the number of tracks in the system database.

4.2 Correct Assignment Ratio

Correct Assignment Ratio measures the performance for a ground truth platform instead of measuring the performance for a track. It assesses the percentage of contacts from a ground truth platform associated with the correct track. The Correct Assignment Ratio of ground truth platform g_i is defined as

$$CAR(g_i) = \left[\sum_{j=1}^{b} C_{ji} \right]^{-1} \max_{1 \leq i \leq b} C_{ji} \tag{4.3}$$

where C_{ji} is the number of the reports originating from the ground truth platform g_i assigned to the track t_j, and b is the number of the tracks generated during the scenario. As for the Track Purity, the calculated MOP, in this work, is the Weighted Average Correct Assignment Ratio (WACAR), a statistic of Correct Assignment Ratio calculated over all tracks and ground truth objects.

$$CAR = \left[\sum_{i=1}^{a} \sum_{j=1}^{b} C_{ji} \right]^{-1} \sum_{i=1}^{a} \max_{j} C_{ji} \tag{4.4}$$

where a is the number of the ground truth platforms presented in the scenario.

4.3 Association Correctness

While Track Purity and Correct Assignment Ration individually may reward imperfect correlation with the maximum score of 1.0, their geometric mean, which will be referred to as Association Correctness (AC), does not. The Association Correctness is defined as

$$\begin{aligned} AC &= \left[(TP)(CAR) \right]^{1/2} && (4.5) \\ &= \left[\sum_{i} \sum_{j} C_{ij} \right]^{-1} \left[\sum_{i} \max_{j} C_{ij} \right]^{1/2} \left[\sum_{j} \max_{i} C_{ij} \right]^{1/2} && (4.6) \end{aligned}$$

It reaches the maximum value of 1.0 if, and only if, each row and each column of the confusion matrix contains exactly one nonzero element, thus indicating the existence of one-to-one identification between the tracks and the ground truth objects, that is a perfect correlation. Note that the defined metrics does not consider the ambiguous measurements (*i.e.*, the ambiguity vector).

4.4 Average Completeness Deviation

Instead of the statistics of the Completeness History, the statistics of its deviation with respect to 1.0 will used. The Completeness Deviation is thus defined as

$$CD(t) = 1 - CH(t) \tag{4.7}$$

Also, to avoid the compensation between negative and positive deviations[2], the average of the absolute values is computed, as follows

$$ACD = \frac{1}{T}\int_0^T |CD(t)|dt \tag{4.8}$$

The standard deviation (Completeness Standard Deviation) is computed as follows

$$CSD = \left[\frac{1}{T}\int_0^T |CD(t) - ACD|^2 dt\right]^{1/2} \tag{4.9}$$

4.5 Credibility

Credibility concerns to what extend one can trust the tracking/fusion system in its self-assessment of its estimation performance, as given by the error covariance matrix. Therefore, an estimator/fusion system is said credible (or consistent), if its stated level of performance is smaller than the actual one [18]. The Credibility is defined here by the two following complementary MOPs [19]. Note that in the sequel where $\boldsymbol{P}$ will represent the actual covariance matrix and $\hat{\boldsymbol{P}}$ its estimate provided by the estimator/fusion system.

1. **Global Credibility Score:** defined as

   $$GCS = \min_i \left\{\lambda_i\right\} = \min_i \left\{eigenvalue\left[\frac{\hat{\boldsymbol{P}} - \boldsymbol{P}}{\boldsymbol{P}}\right]\right\} \tag{4.10}$$

   gives a sufficient qualitative condition for credibility (or non-credibility) of the estimator. If $GCS \geq 0$ the system is credible, otherwise it is non-credible.

2. **(Non)-Credibility Factor:** defined as (if the estimator is credible)

   $$CF = \max_i \left\{\lambda_i\right\} = \max_i \left\{eigenvalue\left[\frac{\hat{\boldsymbol{P}} - \boldsymbol{P}}{\boldsymbol{P}}\right]\right\} \tag{4.11}$$

   and as (if the estimator is not credible)

   $$NCF = \min_i \left\{\lambda_i\right\} = \min_i \left\{eigenvalue\left[\frac{\hat{\boldsymbol{P}} - \boldsymbol{P}}{\boldsymbol{P}}\right]\right\} \tag{4.12}$$

   It gives a quantitative measure of the level of credibility (or non-credibility).

[2] *i.e.*, lack of clarity and lack of completeness.

4.6 Error Reduction

Error Reduction is about the reduction/amplification of the sensor uncertainty by the estimator. It uses two similar MOPs to those used by the credibility [6]. In the sequel, $\boldsymbol{z}$ will represent the measurement vector and $\boldsymbol{R}$ its covariance matrix, while $\boldsymbol{\zeta}$ is the part of the estimation error vector $\tilde{\boldsymbol{x}}$ corresponding to $\boldsymbol{z}$, and $\boldsymbol{\Gamma}$ its covariance matrix. The two MOPs are defined as follows.

1. **Global Error Reduction Score:** defined as

$$GERS = \min_i \left\{ \lambda_i \right\} = \min_i \left\{ eigenvalue \left[\frac{\boldsymbol{R} - \boldsymbol{\Gamma}}{\boldsymbol{R}} \right] \right\} \tag{4.13}$$

   gives a sufficient qualitative condition for sensor error reduction (or amplification) by the estimator. If $GERS > 0$, there is an error reduction in all the dimensions, otherwise there is an amplification in at least one dimension.

2. **Error Reduction/Amplification Factors:** defined as (if there is an error reduction)

$$MERF = \min_i \left\{ \lambda_i \right\} = \min_i \left\{ eigenvalue \left[\frac{\boldsymbol{R} - \boldsymbol{\Gamma}}{\boldsymbol{R}} \right] \right\} \tag{4.14}$$

   gives a quantitative measure of the least good performance (among the state vector dimensions) of the estimator in its error reduction. MERF stands for Minimal Error Reduction Factor. When there is error amplification, the MOP is defined as

$$MEAF = \max_i \left\{ \lambda_i \right\} = \max_i \left\{ eigenvalue \left[\frac{\boldsymbol{R} - \boldsymbol{\Gamma}}{\boldsymbol{R}} \right] \right\} \tag{4.15}$$

   MEAF stands for Maximum Error Amplification Factor and gives a quantitative measure of the worst performance (highest error amplification) of the tracker.

The results of the application of all the above given MOPs to the comparison of the JVC and MHT are presented and discussed in Section 5.

5 Performance evaluation

This section gives the results of the performance evaluation of the MHT and JVC association algorithms within CASE_ATTI test-bed. This comparison uses the set of the MOPs presented in Section 4. First, a summary of the major results and conclusions will be given in Section 5.1, then the detailed evaluation of the two systems will be presented in Section 5.2

5.1 Summary

An important conclusion of this comparison is that the available set of MOPs does not allow stating about any possible improvement in both association and estimation. It was noticed that when association performance increases, estimation performance decreases and vice versa. This problem is clearly visible on the results of Table 9. There is no run that shows a superiority of one approach over the other in both association and estimation. The reasons that could explain thess limitations are:

1. the independence assumption, between the association and estimation operations, that was made during the selection of the MOPs. It is however obvious that the two operations are tightly dependent, and evaluating one without considering the other is senseless. A good state estimation is impossible without an equally good contact-to-track association strategy, and vice versa. Inaccurate tracks give an inefficiently accurate state prediction, that lead to significant errors in the gating/association of contacts with tracks.

2. the type of analysis applied that is based on implicit independence assumption[3] between association and update phases, and which uses only common portions of the tracks for the comparison. Such an approach penalizes, in terms of estimation MOPs, the solution/system that keeps continuous tracks (*i.e.*, yields a good performance in association) even when the accuracy decreases below the contact accuracy (due mainly to manoeuvres). The reverse is also true; a system with a poor performance in association will produce several tracks for each target, with an accuracy that is higher (at least equal to the contact one) than that of single continuous track. This problem was noticed is several situations with both simulated and real world data.

The solution to this problem would consist of using the whole run for the evaluation of the performance and finding a way to combine association MOPs, particularly the track continuity MOP, with the estimation MOPs in order to penalize the track mis-association (discontinuity) when evaluating the track accuracy. Given this limitation, it would not be very judicious to perform an in depth analysis of the estimation performance. Therefore, the analysis will be only performed on the association MOPS. Nonetheless, results for the evaluation of the estimation MOPs will be given for completeness, and used only if further insight on the performance of the algorithms is required.

[3] Given the nature of the used MOPs.

Since each run has its particular configuration, such as the number of targets, the type of targets, and the performed manoeuvres, none of the two algorithms performs well for all runs. Table 9 shows the comparison results, in term of association and estimation performance for each run. In conflicting situations, more importance is accorded to the association performance.

Run	Association Superiority	Estimation Superiority
1	$\equiv$	MHT
1b	$\equiv$	MHT
2	**JVC**	**MHT**
3	**MHT**	JVC
7&8	**MHT**	**JVC**
9	$\equiv$	**JVC**
12 & 13	$\equiv$	**JVC**

Table 9: *Comparison of MHT and JVC algorithms by Run for all MOPs*

It is clear from the presented results that there is no real advantage of one approach over the other, even though MHT shows a slight superiority with association MOPs and JVC a slight superiority in estimation. Note that, in all presented tables, bold face indicates a noticeable superiority, while normal face indicates a slight superiority. Details of the comparison are given in Section 5.2.

The same conclusion can be drawn from the Table 10 that shows, for all runs, the aggregated results of each MOPs. While the MHT is superior for some MOPs, JVC performs better for the other MOPs.

MOP	Superiority
TP	**JVC**
CAR	**MHT**
AC	**MHT**
ACD	**JVC**
Cr	MHT
Er	$\equiv$

Table 10: *Comparison of MHT and JVC algorithms by MOP for all runs*

5.2 Detailed results

This section presents the detailed results of the performance evaluation of the two configurations using the different MOPs presented in Section 4.

5.2.1 Association MOPs

Table 11 summarizes the results of this evaluation with the different association MOPs. Track Purity and Correct Assignment Ratio are then aggregated therein into a single MOP, namely the Association Correctness, as presented in Section 4.3. From association perspective, the analysis boils therefore down to comparing the two algorithms using only two MOPs: the Association Correctness and Average Completeness Deviation (See Section 4.4).

The results of Table 11 show no real advantage of one algorithm over the other. While JVC performs well in term of Average Completeness Deviation, MHT is superior in the Association Correctness.

Run	TP	CAR	AC	ACD	Superiority
1	**JVC**	**MHT**	**MHT**	**JVC**	≡
1b	JVC	MHT	MHT	JVC	≡
2	MHT	**JVC**	JVC	**JVC**	**JVC**
3	≡	**MHT**	**MHT**	≡	**MHT**
7 &8	MHT	**MHT**	**MHT**	≡	**MHT**
9	**JVC**	**MHT**	**MHT**	**JVC**	≡
12 & 13	**JVC**	**MHT**	**MHT**	**JVC**	≡

Table 11: *Association MOPs*

Table 12 shows the scores of the two algorithms for the Track Purity, for each run. As previously stated, there is no real advantage of one algorithm over the other.

Run	JVC	MHT	MHT with Clusters	Superiority
1	.903	—	.788	**JVC**
1b	.901	.896	—	JVC
2	.931	.943	—	MHT
3	.998	.998	—	≡
7 & 8	.920	.936	.930	MHT
9	.902	.862	—	**JVC**
12 & 13	.925	—	.889	**JVC**

Table 12: *Track Purity*

Table 13 shows the values of Correct Assignment Ratio MOP of each run, where MHT seems to be superior to JVC in most situations. Table 14 shows the values for the aggregated Association Correctness MOP. MHT maintains its superiority due to its higher performance with Correct Assignment Ratio.

The Average Completeness Deviation MOP, and its variance, are computed for the different runs, and results are summarized on Table 15. These results show a better performance of the JVC over the MHT.

Run	JVC	MHT	MHT with Clusters	Superiority
1	.278	—	.579	**MHT Cl.**
1b	.385	.418	—	MHT
2	.413	.334	—	**JVC**
3	.507	.661	—	**MHT**
7 & 8	.411	.487	.920	**MHT Cl.**
9	.360	.484	—	**MHT**
12 & 13	.275	—	.486	**MHT Cl.**

Table 13: *Correct Assignment Ratio*

Run	JVC	MHT	MHT with Clusters	Superiority
1	0.501	—	0.676	**MHT Cl.**
1b	0.589	0.612	—	MHT
2	0.620	0.561	—	JVC
3	0.711	0.813	—	**MHT**
7 & 8	0.615	0.675	.926	**MHT Cl.**
9	0.570	0.646	—	**MHT**
12 & 13	0.505	—	0.657	**MHT Cl.**

Table 14: *Association Correctness*

Run	JVC	MHT	MHT with Clusters	Superiority
1	$0.016_{0.008}$	—	$0.350_{0.072}$	**JVC**
1b	$0.037_{0.017}$	$0.062_{0.040}$	—	JVC
2	$0.024_{0.023}$	$0.469_{0.239}$	—	**JVC**
3	$0.000_{0.000}$	$0.000_{0.000}$	—	$\equiv$
7 &8	$0.027_{0.026}$	$0.025_{0.024}$	$0.051_{0.035}$	$\equiv$
9	$0.020_{0.011}$	$0.139_{0.057}$	—	**JVC**
12 & 13	$0.043_{0.020}$	—	$0.151_{0.069}$	**JVC**

Table 15: *Completeness History* (ACD_{Variance})

5.2.2 Estimation MOPs

Table 16 summarizes the results for two estimation MOP, namely the Credibility (see Section 4.5 for definition) and the Error Reduction (see Section 4.6 for definition). The objective here is not an in depth comparison of the two approaches. Since MHT and JVC are association algorithms, this comparison aims at showing how the performance of the association algorithm affects the estimation one. From this perspective, JVC shows marginally better behaviour.

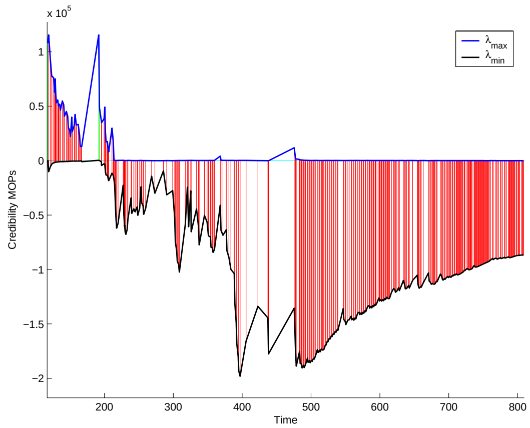
Table 17 gives the percentage of time during which the system was credible in its self-assessment of the tracking performance. This MOP is only based on GCS MOP. To better

Run	Target	Credibility	Error Reduction	Superiority
1	S80	JVC	≡	JVC
	S546	**MHT**	**MHT**	**MHT**
1B	S80	MHT	≡	MHT
	S546	**MHT**	≡	**MHT**
2	S80	JVC	**MHT**	MHT
	S546	**MHT**	**MHT**	**MHT**
3	S80	**JVC**	JVC	**JVC**
	S546	≡	≡	≡
7 &8	T1	≡	≡	≡
	T2	≡	JVC	JVC
9	T1	≡	≡	≡
	T2	≡	**JVC**	**JVC**
12&13	S80	JVC	**JVC**	**JVC**
	S546	MHT	**JVC**	JVC

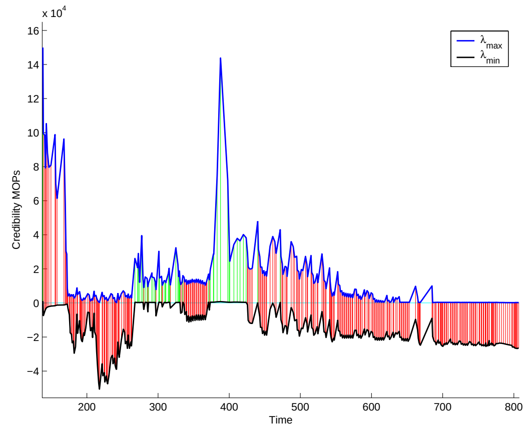
Table 16: *Comparison for estimation MOPs*

show the CF and NCF notions, color bars (respectively green and red) are used on the presented graphics. According to the scores of Table 17, none the two algorithms yields a good performance in term of credibility.

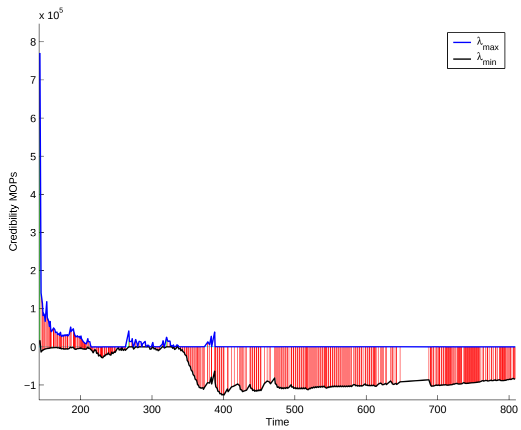
Similarly, Table 18 gives the percentage of time during which there was a reduction of the sensor uncertainty by the tracking/fusion system. As for the Credibility, Table 18 does not reveal any good performance from the two approaches in terms of error reduction. Since the values represent the percentage of time during which there is a reduction of uncertainty, a low value means the system are not reducing error during most of time. As shown on Table 18, MHT and JVC obtain approximately the same level of values in most of the cases, the differences are not more than 2% or 3%.



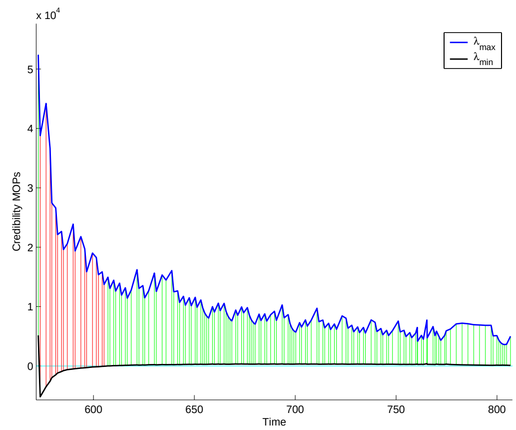
(a) JVC - S80



(b) JVC - S546

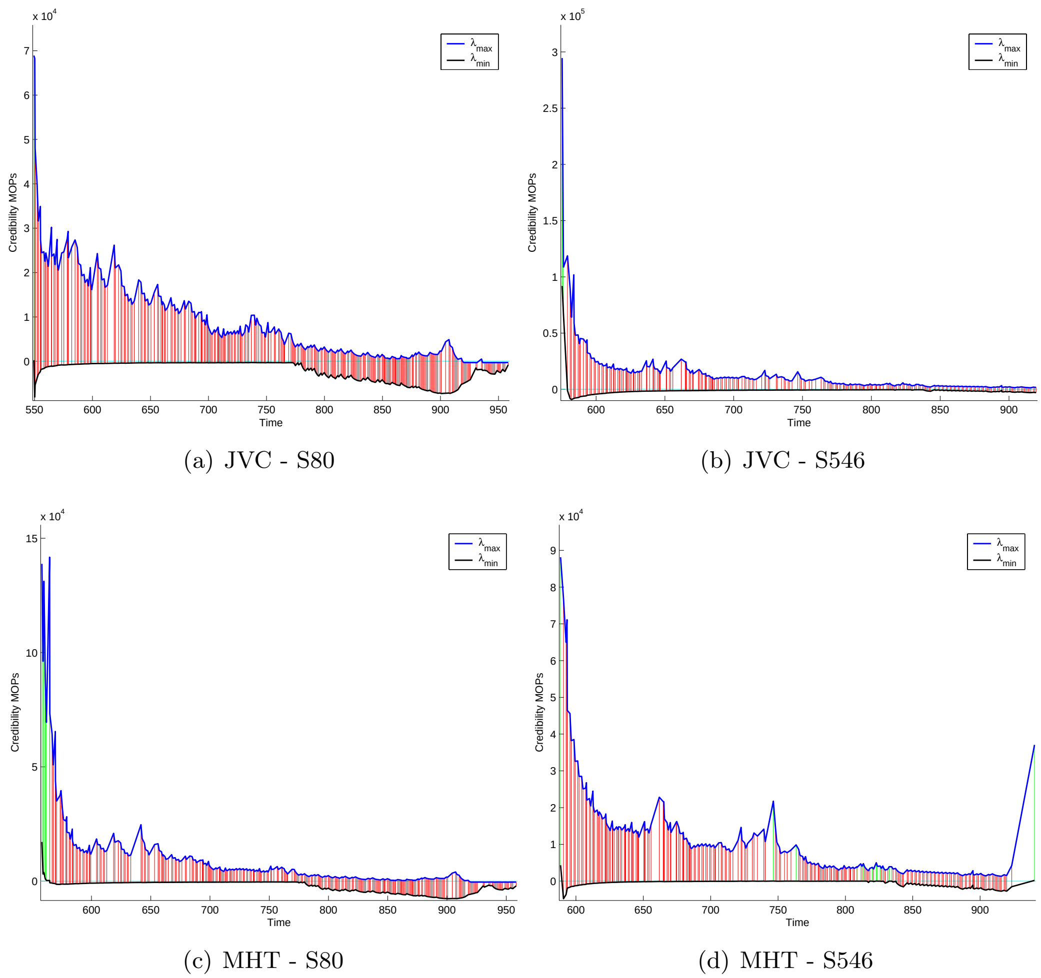


(c) MHT - S80



(d) MHT - S546

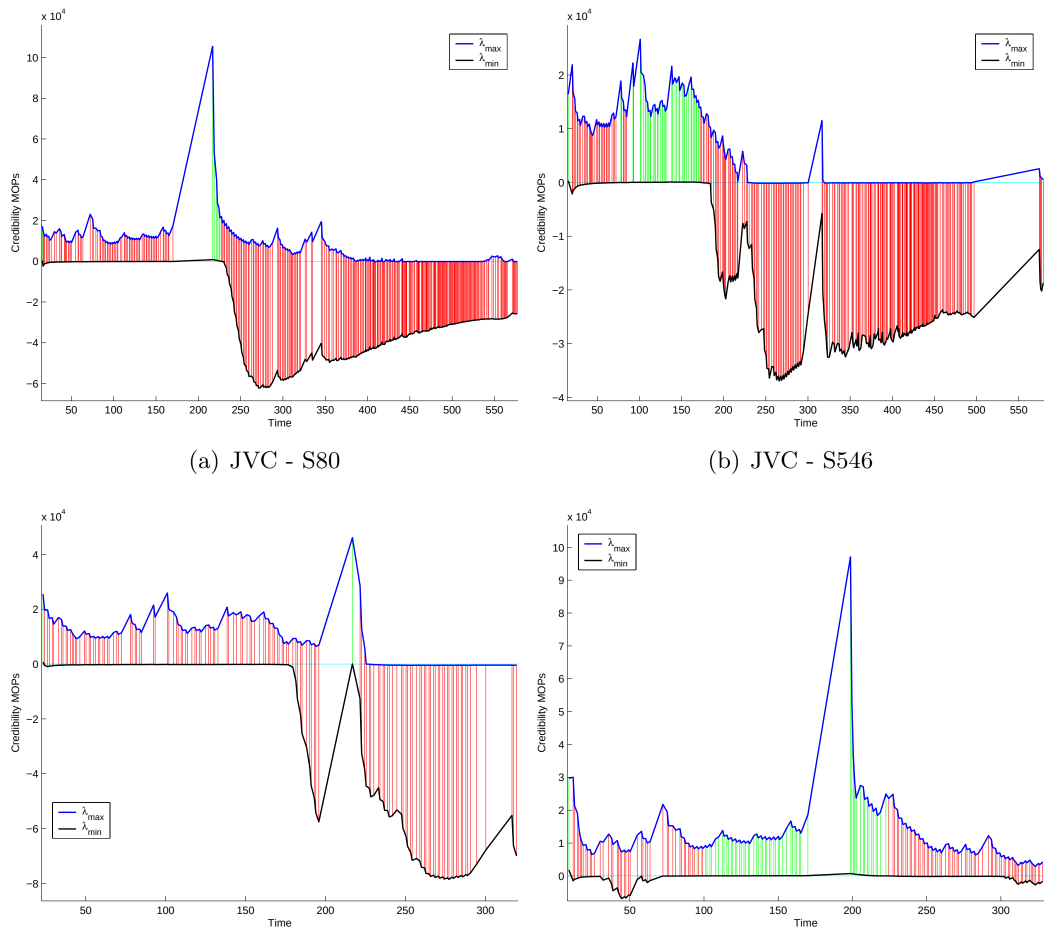
Figure 12: *Credibility for Run 1*



(a) JVC - S80 (b) JVC - S546

(c) MHT - S80 (d) MHT - S546

Figure 13: *Credibility for Run 1B*



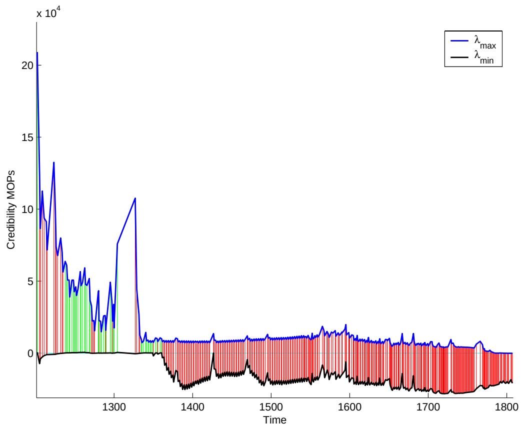
(a) JVC - S80

(b) JVC - S546

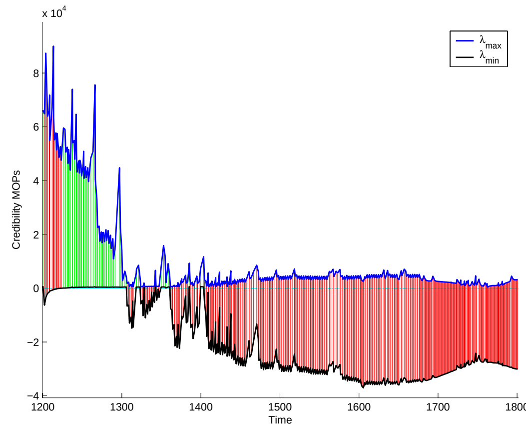
(c) MHT - S80

(d) MHT - S546

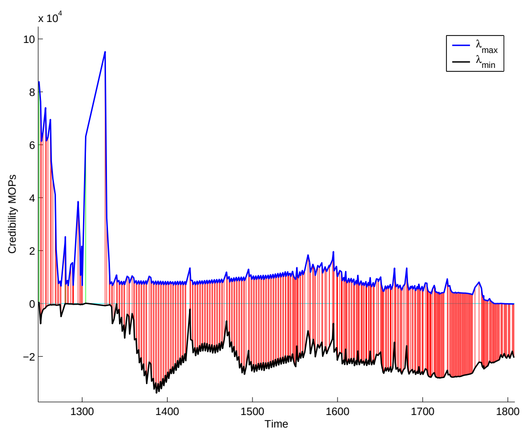
Figure 14: *Credibility for Run 2*



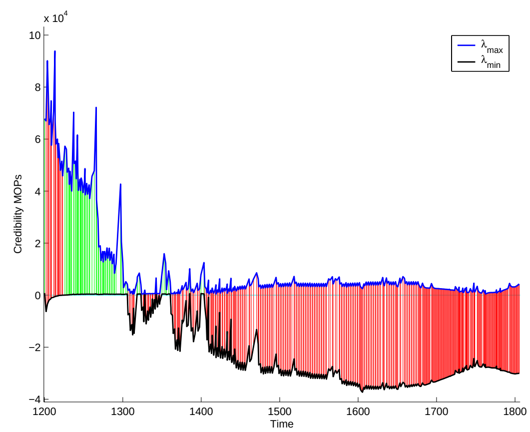
(a) JVC - S80



(b) JVC - S546

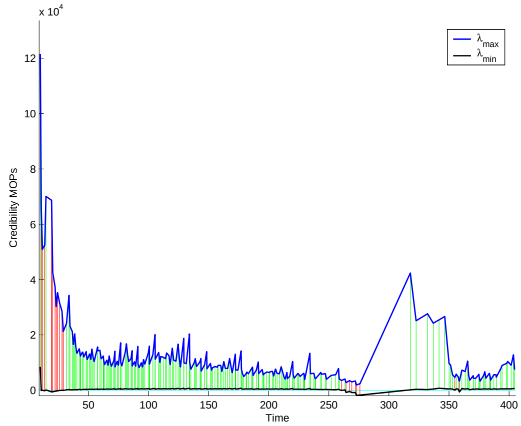


(c) MHT - S80

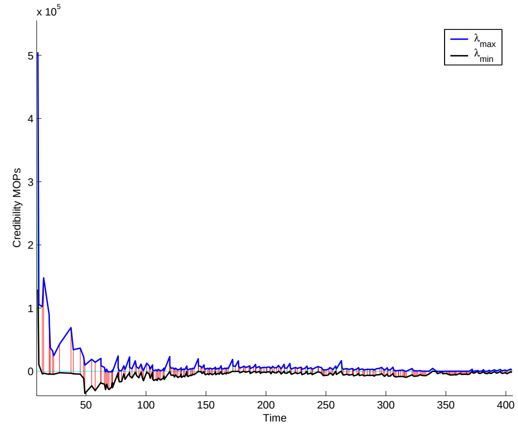


(d) MHT - S546

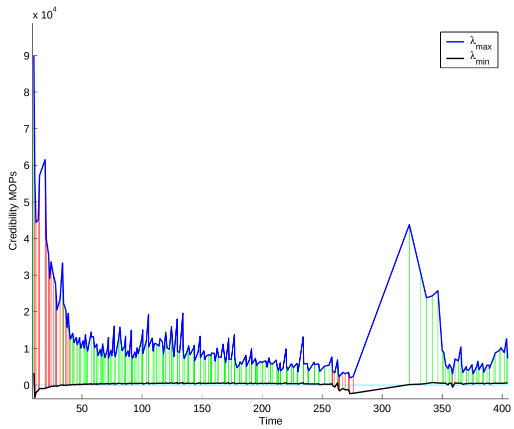
Figure 15: *Credibility for Run 3*



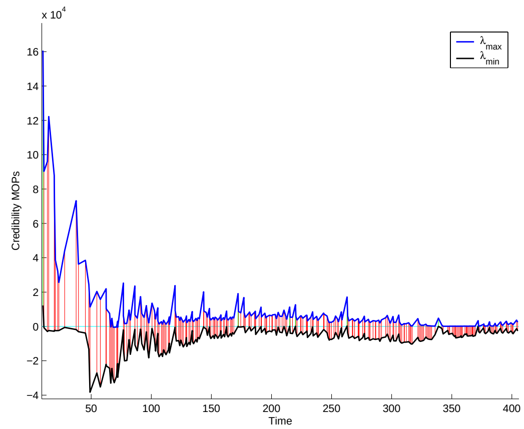
(a) JVC - T1



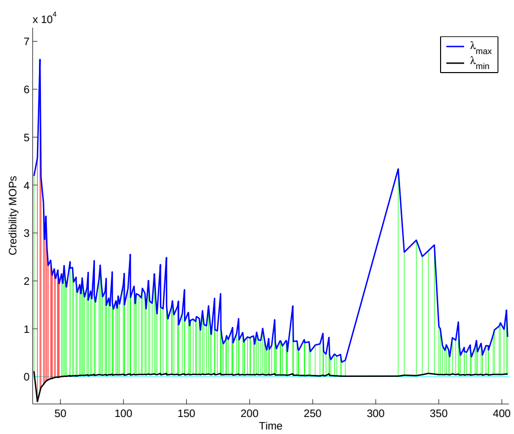
(b) JVC - T2



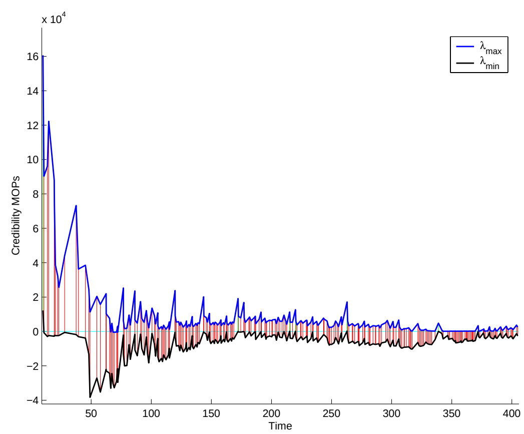
(c) MHT - T1



(d) MHT - T2

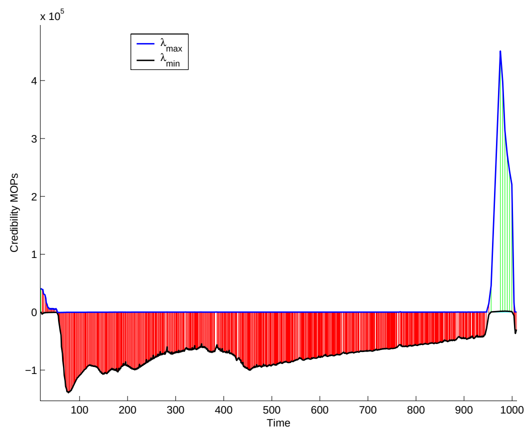


(e) MHT (with clustering) - T1

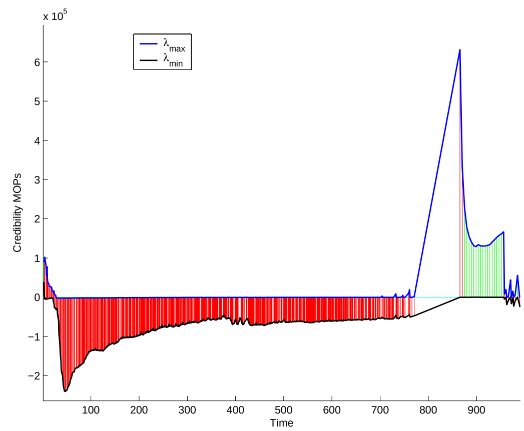


(f) MHT (with clustering) - T2

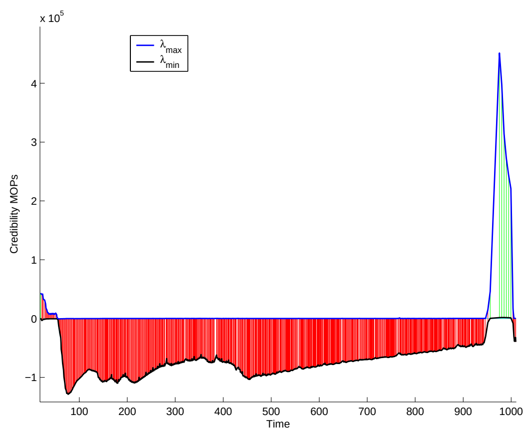
Figure 16: *Credibility for Runs 7 & 8*



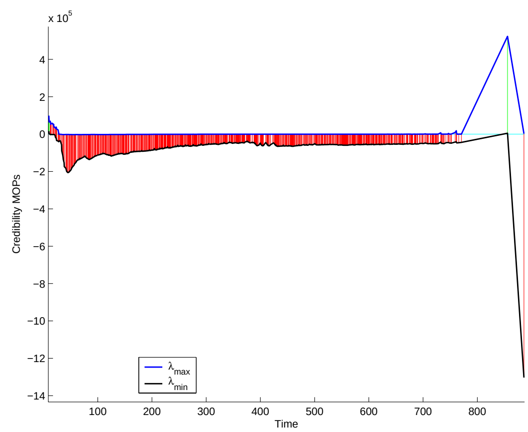
(a) JVC - T1



(b) JVC - T2

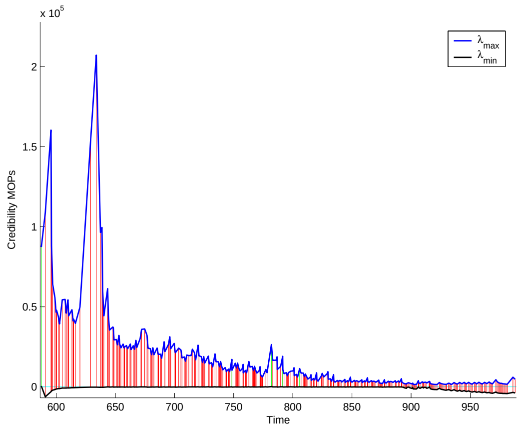


(c) MHT - T1

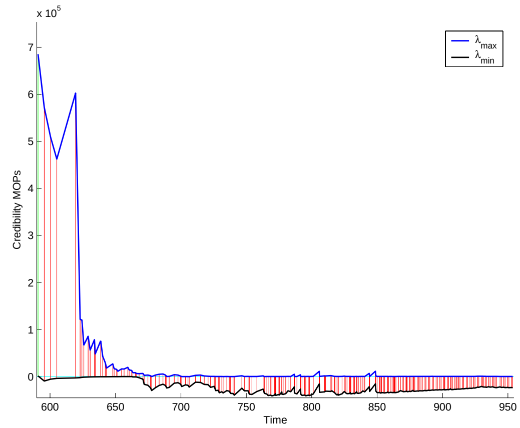


(d) MHT - T2

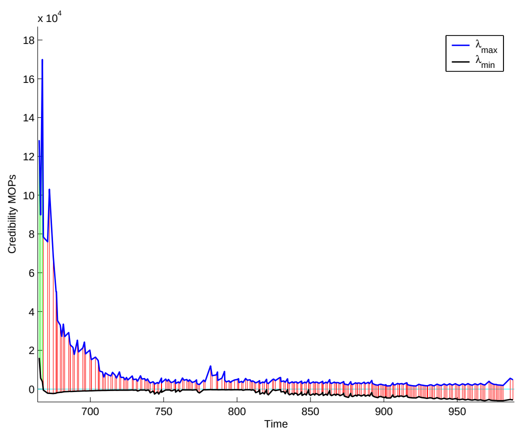
Figure 17: *Credibility for Run 9*



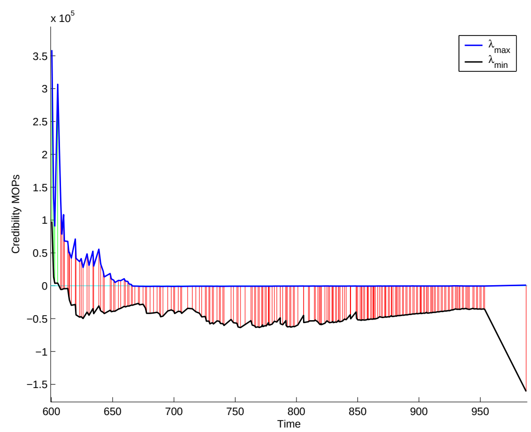
(a) JVC - S80



(b) JVC - S546

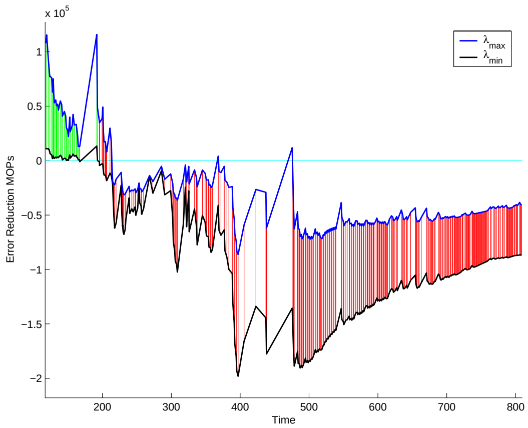


(c) MHT - S80

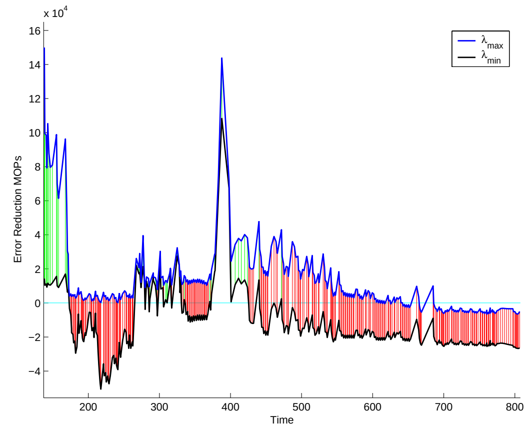


(d) MHT - S546

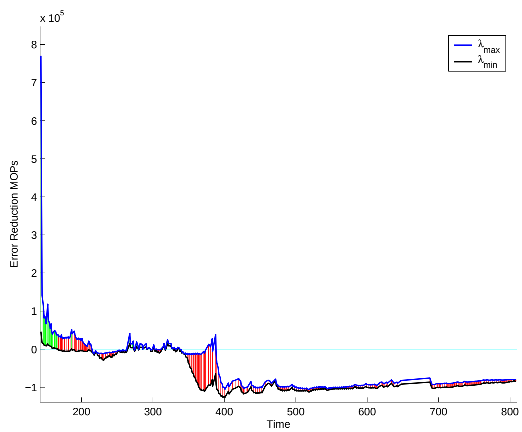
Figure 18: *Credibility for Runs 12 & 13*



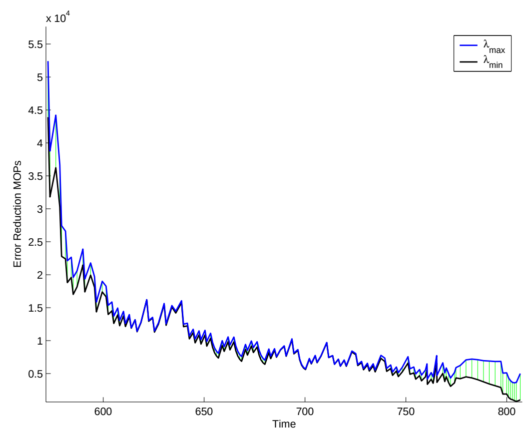
(a) JVC - S80



(b) JVC - S546

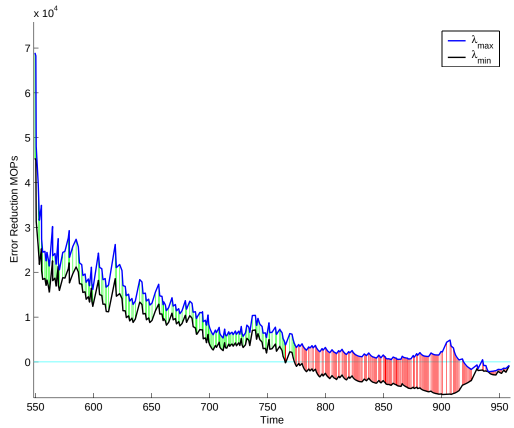


(c) MHT - S80

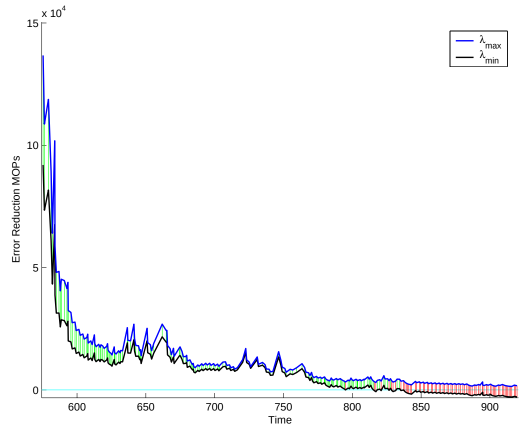


(d) MHT - S546

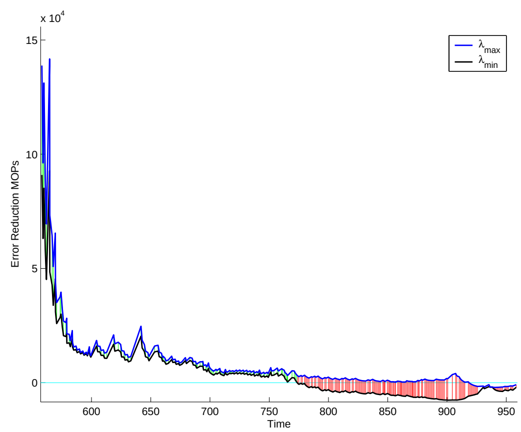
Figure 19: *Error Reduction for Run 1*



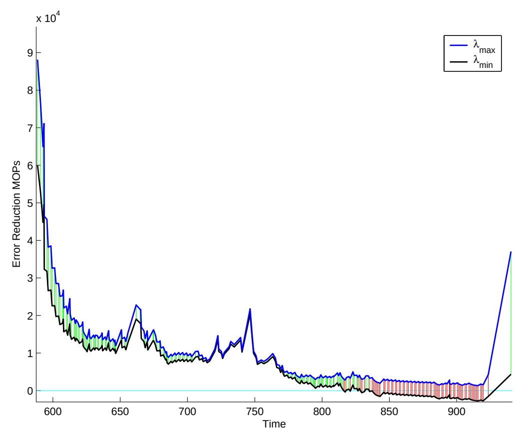
(a) JVC - S80



(b) JVC - S546

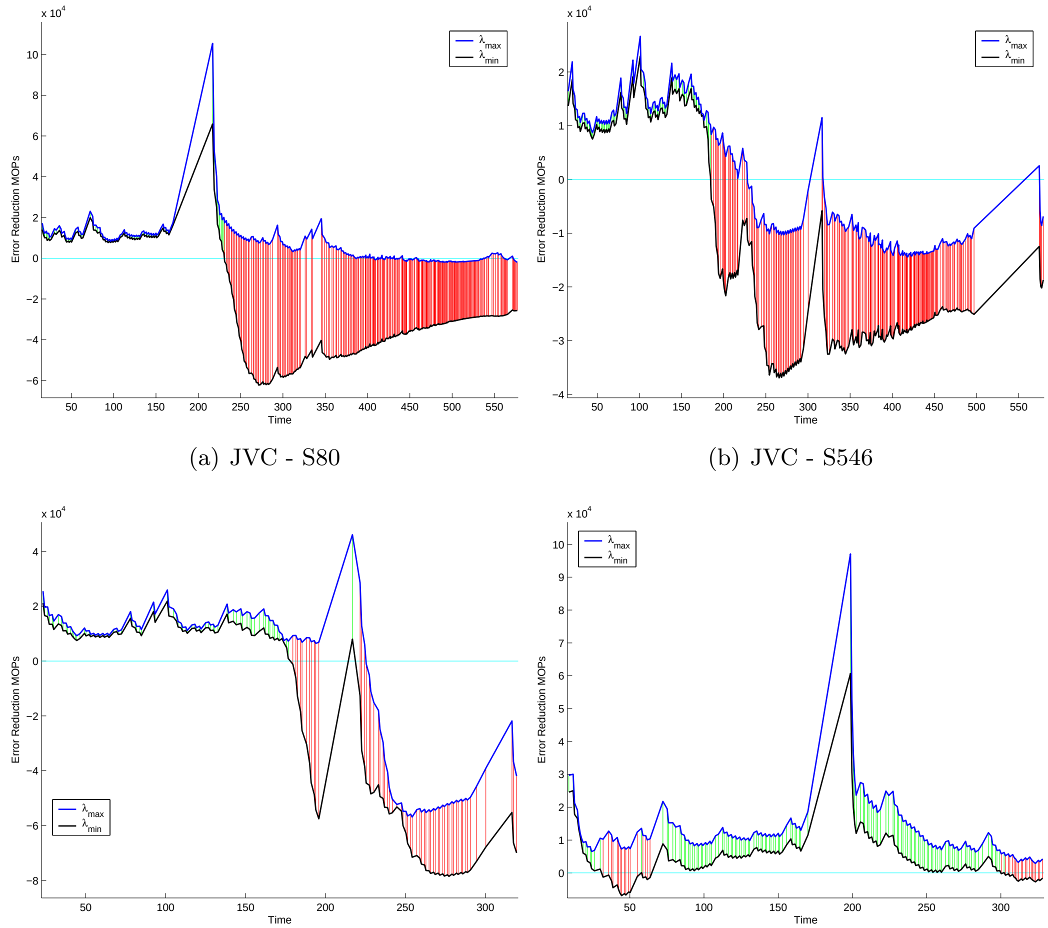


(c) MHT - S80



(d) MHT - S546

Figure 20: *Error Reduction for Run 1B*



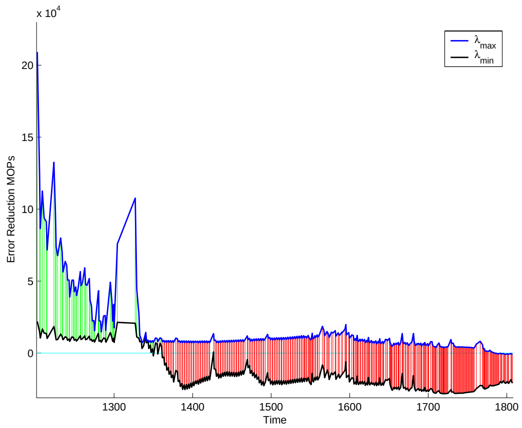
(a) JVC - S80

(b) JVC - S546

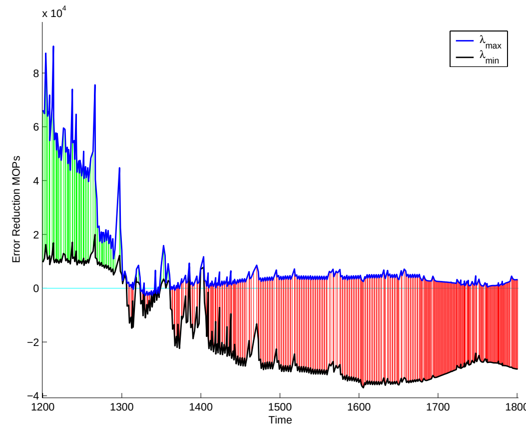
(c) MHT - S80

(d) MHT - S546

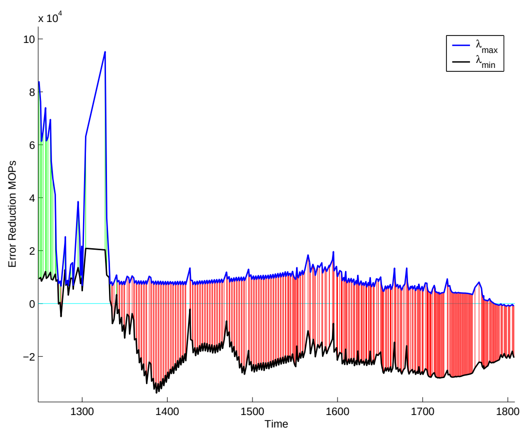
Figure 21: *Error Reduction for Run 2*



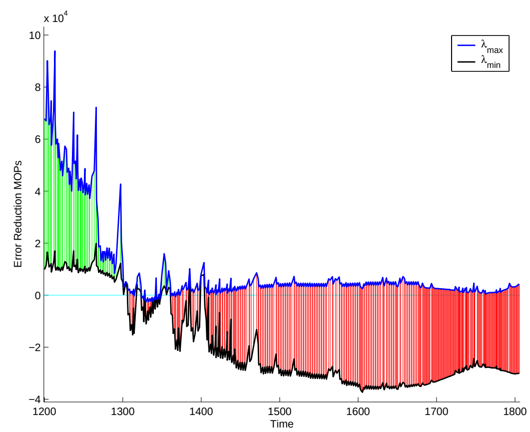
(a) JVC - S80



(b) JVC - S546

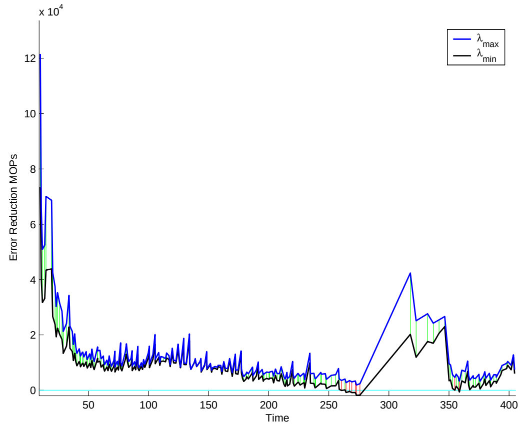


(c) MHT - S80

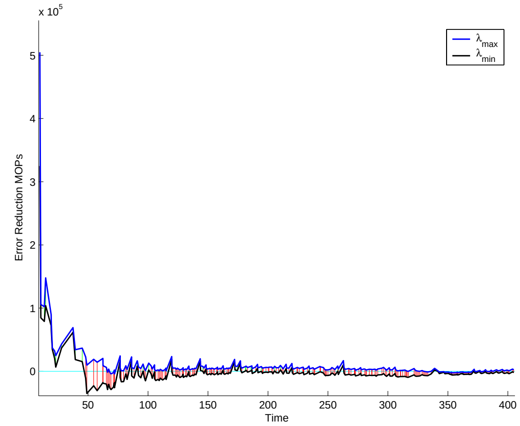


(d) MHT - S546

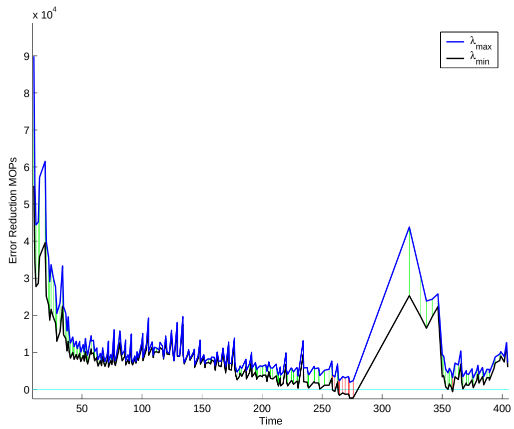
Figure 22: *Error Reduction for Run 3*



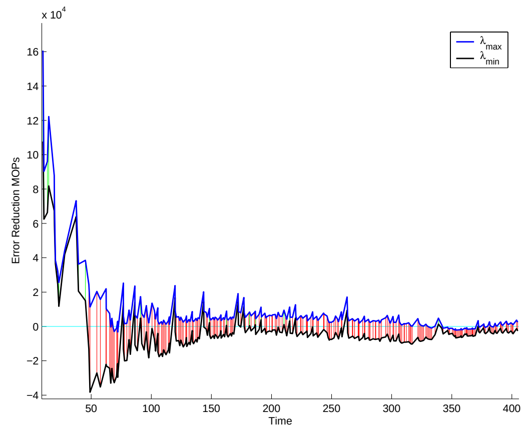
(a) JVC - T1



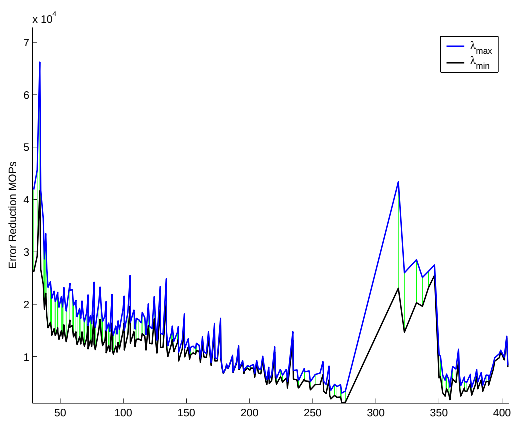
(b) JVC - T2



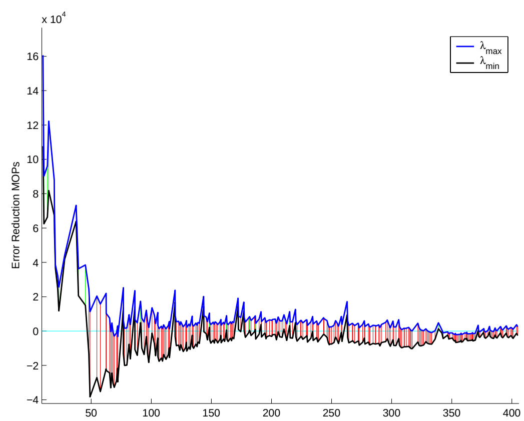
(c) MHT - T1



(d) MHT - T2

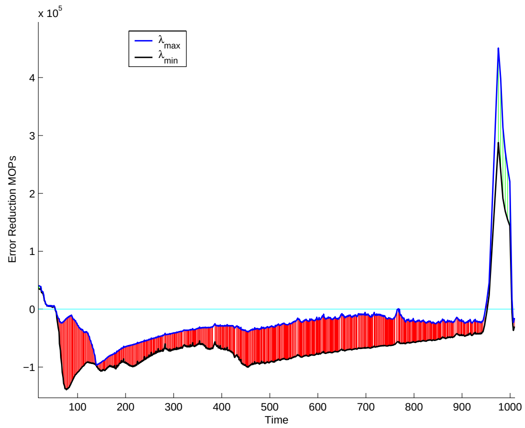


(e) MHT (with clustering) - T1

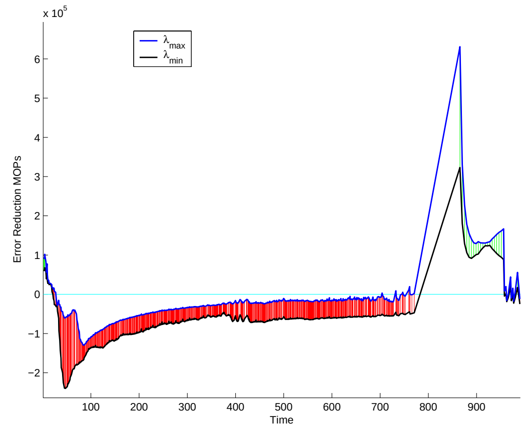


(f) MHT (with clustering) - T2

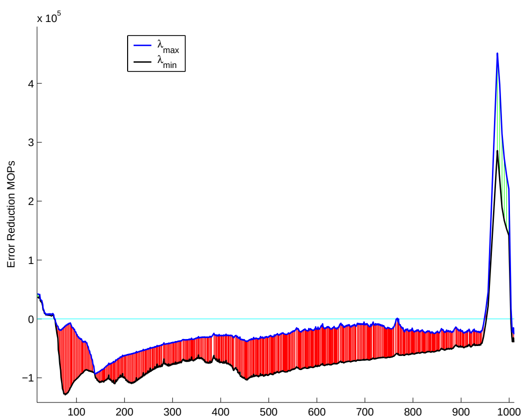
Figure 23: *Error Reduction for Runs 7 & 8*



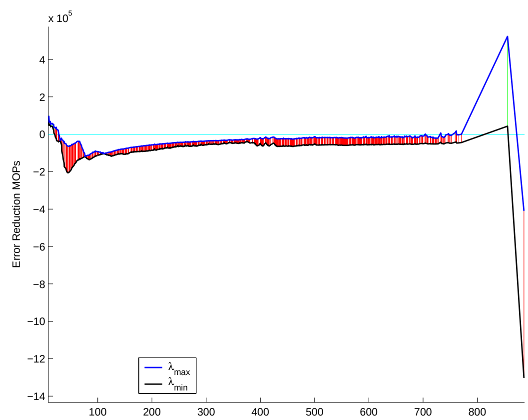
(a) JVC - T1



(b) JVC - T2



(c) MHT - T1



(d) MHT - T2

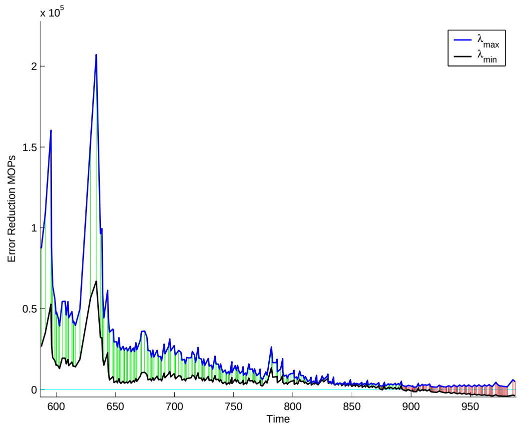
Figure 24: *Error Reduction for Run 9*

Run	Target	JVC	MHT	Superiority
1	S80	3.72	1.18	JVC
	S546	19.74	86.06	**MHT**
1B	S80	0.0	1.63	MHT
	S546	0.29	12.21	**MHT**
2	S80	9.87	7.10	JVC
	S546	16.15	39.87	**MHT**
3	S80	14.42	0.82	**JVC**
	S546	19.06	18.91	$\equiv$
4	S80	16.18	22.87	**MHT**
	S546	90.12	90.50	$\equiv$
7 &8	T1	91.08	89.12	$\equiv$
	T2	5.70	4.53	$\equiv$
9	T1	4.84	4.84	$\equiv$
	T2	9.66	9.80	$\equiv$
11	S80	35.29	22.79	**JVC**
	S546	0.41	38.15	MHT
	E1	0.0	1.62	MHT
	E2	30.87	23.86	**JVC**
	E3	17.63	18.08	$\equiv$
12&13	S80	2.28	0.67	JVC
	S546	0.0	1.23	MHT

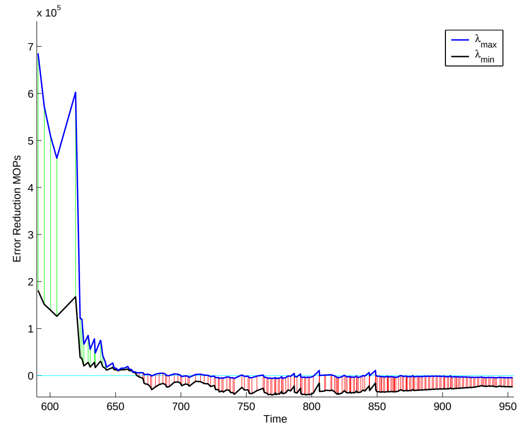
Table 17: *Percentage Time of Credibility*

Run	Target	JVC	MHT	Superiority
1	S80	10.82	11.82	≡
	S546	24.88	100.0	**MHT**
1B	S80	54.41	53.69	≡
	S546	72.79	72.51	≡
2	S80	38.23	58.89	**MHT**
	S546	29.94	81.94	**MHT**
3	S80	26.66	15.13	**JVC**
	S546	22.89	22.71	≡
4	S80	51.40	52.00	≡
	S546	93.03	93.17	≡
7 &8	T1	95.64	95.84	≡
	T2	26.91	21.12	JVC
9	T1	8.23	8.33	≡
	T2	21.82	10.79	**JVC**
11	S80	39.98	35.33	JVC
	S546	36.84	43.89	**MHT**
	E1	0.0	8.63	**MHT**
	E2	32.43	32.45	≡
	E3	26.17	23.95	JVC
12&13	S80	76.11	40.50	**JVC**
	S546	20.77	2.63	**JVC**

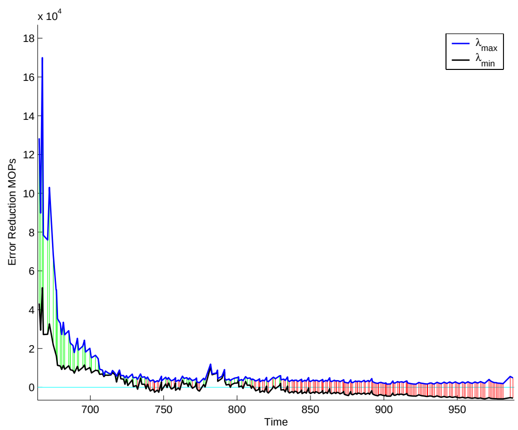
Table 18: *Percentage of Time of Error Reduction*



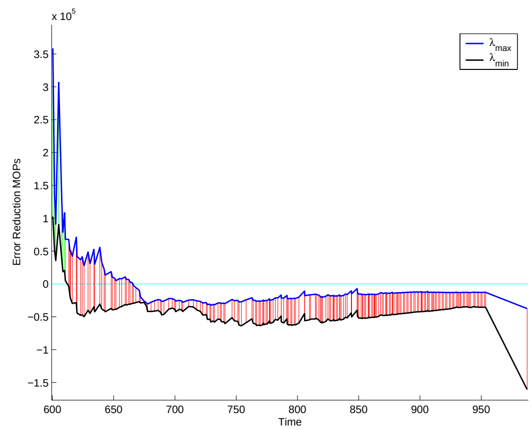
(a) JVC - S80



(b) JVC - S546



(c) MHT - S80



(d) MHT - S546

Figure 25: *Error Reduction for Runs 12 & 13*

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6 Conclusion

This report presents the results of the work performed, at DRDC Valcartier, as a part of the performance evaluation of COMDAT MSDF technology. A previously performed data analysis showed a limited performance of COMDAT MSDF with respect to the association. This work aims at evaluating a candidate alternative to the JVC algorithm used by MSDF, namely the MHT, a equivalent implementation of which is available in CASE_ATTI test-bed. The latter is used as a comparison environment. This comparison uses a limited set of MOPs and was conducted under time and resources constraints, during the June–August, 2003 time frame. Therefore, the presented results and the following conclusions should be considered in the light of those constraints.

1. Even though it is proved theoretically, and using synthetic data, that the MHT offers an optimal solution to the association algorithm, the presented results show no real advantage, with real world data, of MHT over JVC.

2. Implementation, optimization (of the code), and the parameter tuning of the MHT algorithm is costly (both in terms of time and money). These results are optimized to the extent that each algorithm was tuned for each run. If parameters had been tuned to some nominal values and then held constant over all runs then the resulting performance may be worse, and comparison of the two algorithms may be at the advantage of the JVC, since it is less sensitive to the parameter tuning.

3. Behaviour of the MHT with real world data is still not well understood. More sensitivity analysis is required to gain a clear idea of how the MHT could work in a practice. A badly coded/tuned/used MHT may yield worse results than the simple Nearest Neighbour algorithm. This was the case with MHT when compared with the JVC that is easier to tune.

4. Rather than investigating/envisaging the implementation of new complex algorithms in COMDAT MSDF, it would be more judicious and safer to understand why the JVC did not yield the expected performance with real world data. A better tuning might be required.

5. The improvement of other functionalities, such the gating and the estimation, may help increase the performance of the association algorithm. The use of a different metrics may be used to improve the gating performance, and therefore the association.

It important to notice that this work represents an initial investigation that leaves a number of questions unanswered. These questions are being addressed by COMDAT TDP team, mainly at DRDC Atlantic.

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